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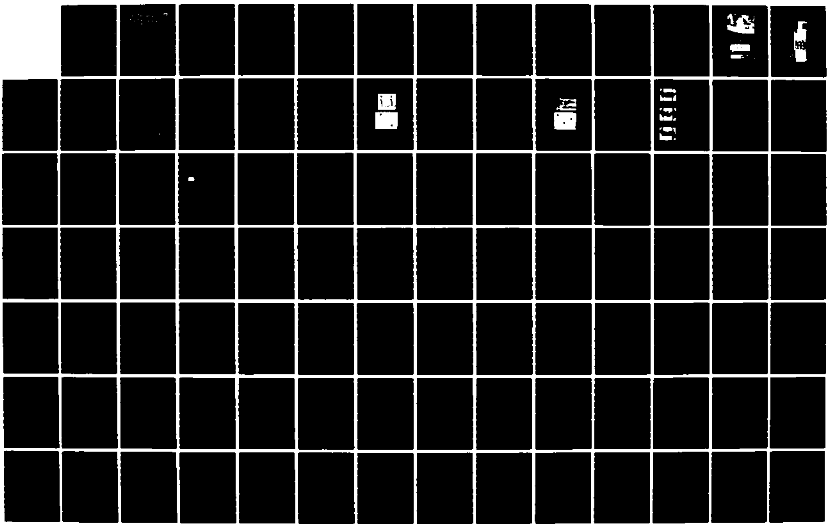

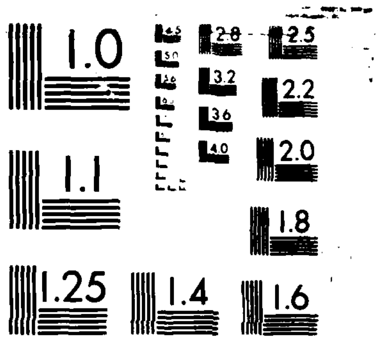
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Soldering Technology & PRODUCT ASSURANCE

PROCEEDINGS

OF

7TH ANNUAL SEMINAR

23, 24, 25 FEBRUARY 1983

This is an informal report containing preliminary information. It is not an official report of the Naval Weapons Center and must not be used as a basis for action unless enclosed in official correspondence in which the purpose of the transmittal is made clear.

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NAVAL WEAPONS CENTER
CHINA LAKE, CALIFORNIA
93555

DEPARTMENT OF THE NAVY
NAVAL WEAPONS CENTER
CHINA LAKE, CALIFORNIA 93555

IN REPLY REFER TO

Thank you for your interest in soldering technology, and your attendance at this seminar.

It is vital that we maintain a continued interest and attempt to resolve our many production problems prior to adverse effects on fleet hardware. It is necessary that we design for ease of manufacturing and it is necessary that we eliminate the unjustified amounts of touch-up that is going on throughout industry today. The only way that this can be done is to understand our many problems and admit that they are there, then do something to eliminate them - corrective measures.

During our next two years, we plan heavy emphasis on automation, in fulfillment of the block diagram approach that you saw in our 4th, 5th, and 6th seminars. The contract will be let within the next two months. It is our hope that this program will result in total automation. Keep up with this program, CCAPS.

The 8th Annual Seminar will be titled "Product Assurance", which entails Soldering Technology, Quality Assurance, Reliability, Safety, and Metrology. If you have an interest in presenting a paper on next year's program, please submit your abstract not later than 1 October 1983 and plan for your complete paper to arrive at the Naval Weapons Center by 9 January 1984.

The dates for the 1984 seminar have not been established yet, however, everyone present at this seminar will receive an invitation.

7TH ANNUAL SOLDERING TECHNOLOGY/PRODUCT ASSURANCE SEMINAR

"Automatic Solder Joint Inspection in Depth"
Ricardo Vanzetti, Vanzetti Corporation, Stoughton, Massachusetts

"Customizing: The Key to Effective Safety Requirements"
William J. Smith, McDonnell Douglas, St. Louis, Missouri

"The Effect of Measurement Accuracies and Calibrations on Product Quality and Productivity"
Rolf B.F. Schumacher, Rockwell International, Anaheim, California

"Calibration: The Essential Ingredient of an Effective Total Quality Assurance"
Phil Painchaud, Metron Corporation, Rancho Cucamonga, California

"Cleaning Printed Wiring Assemblies with Isopropyl Alcohol - an Attractive Alternative to Conventional Cleaning Solvents"
Scott Goepfert, Honeywell, Hopkins, Minnesota

"Quality Assurance: Cost Driver or Cost Saver"
Robert Moore, NWC Quality Assurance

"Vapor Phase Soldering of Chip Devices"
Christian Val, Hybrid Microelectronics, Thomson-CSF, Velizy, France

"Creep and Fatigue Testing of Micro Solder Joints"
Gert Becker, L.M.Ericsson, Stockholm, Sweden

"Particle Impact Noise Detection as a Production Screen"
Robert Martin, General Dynamics, Pomona, California

"Particle Impact Noise Detection in Devices with Internal Cavities"
Jack Brown, B&W Engineering, Costa Mesa, California

"Reducing the Solder Defect Rate on Printed Wiring Assemblies"
J. Gordon Davy, Westinghouse, Columbia, Maryland

"Printed Wiring Board Solderability"
Roy Yenowine, Texas Instruments, Lewisville, Texas

"Automatic Insertion in Military Industry"
Tom Kempton, Raytheon, Lowell, Massachusetts

"Plating Effect on Component Solderability and Solder Joint Strengths"
Roger Wild, IBM, Owego, New York

"Solderability Defect Recognition for Solderability Tested Component Leads"
Al Fitak, Litton Guidance and Control, Woodland Hills, California

"Analysis of Solder Joint Inspection and Rework Methods"
John DeVore, General Electric, Syracuse, New York

"Transitioning Engineering Designs to Production"
Ezra Sheffres, Raytheon, Lexington, Massachusetts

"The Hidden Factory"
Jim Kuhlemeir & Garland Linde, Honeywell, Hopkins, Minnesota

"Organizational Structure - The Effectiveness of the Quality Function"
Charles Seeger, General Dynamics, Pomona, California

"Determination of Relative Activity and Pot Life of Soldering Flux Using Wetting Balance Techniques"
John Rizzo, Boeing Aerospace Company, Seattle, Washington

"Solder Training at Hughes Aircraft Company Tucson Manufacturing Division"
Gwen Markham, Hughes Aircraft, Tucson, Arizona

"Wave Solder Audit System - A Tool for Process Control"
Tom Wurzburger, Santa Barbara Research Center, Goleta, California

AUTOMATIC SOLDER JOINT INSPECTION IN DEPTH

Riccardo Vanzetti and Alan C. Traub
Vanzetti Systems, Inc., Stoughton, Massachusetts 02072

Presented at the

Seventh Annual Soldering Technology Seminar
23, 24, 25 February 1983

Naval Weapons Center
China Lake, California 93555

AUTOMATIC SOLDER JOINT INSPECTION IN DEPTH

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AUTOMATIC SOLDER JOINT INSPECTION IN DEPTH

Riccardo Vanzetti and Alan C. Traub
Vanzetti Systems, Inc., Stoughton, Massachusetts 02072

ABSTRACT

A sensitive infrared detection system monitors the slight warming and cooling of a solder joint in response to a focused laser-beam pulse lasting for 30 milliseconds (ms). Heating and cooling rates are dependent upon solder surface finish and internal features. The rates are computer-sorted in order to distinguish between normal and defective joints, and the latter are flagged in a printout. Inspection is at the rate of 10 joints per second. By statistical processing of the data, board-to-board quality variations are revealed in quasi-real time, thus enabling tight process control of the soldering operation.

INTRODUCTION

In the mid-1970's, an interesting series of tests was performed at Hills Air Force Base in Ogden, Utah. The Technical Repair Center, there, is charged with maintenance of the F-111 aircraft Mark II electronic PC boards. In the tests, a group of 159 randomly chosen, defective boards which had been returned from the field were diagnosed and the necessary repairs were made. It was discovered that 50% of the boards could be made fully operable by re-work of faulty solder joints only.

Had an automatic inspection system been available at the time of manufacture, one which was able to find both visible and hidden defects, most of these field failures might have been avoided, reducing the cost of maintenance by up to 50%. In the particular case of the F-111, the savings could be several million dollars annually.

Shortly after these tests, the Air Force Logistics Command began an active exploration, under the direction of engineer John Ele at Sacramento, of various avenues which might lead to the availability of such an inspection system. Responding to this need, Vanzetti Systems, Inc., undertook an active development program in 1977 which culminated, five years later, in their introducing the Model Li/6000 Laser/INSPECT system for automatic testing of solder joints.

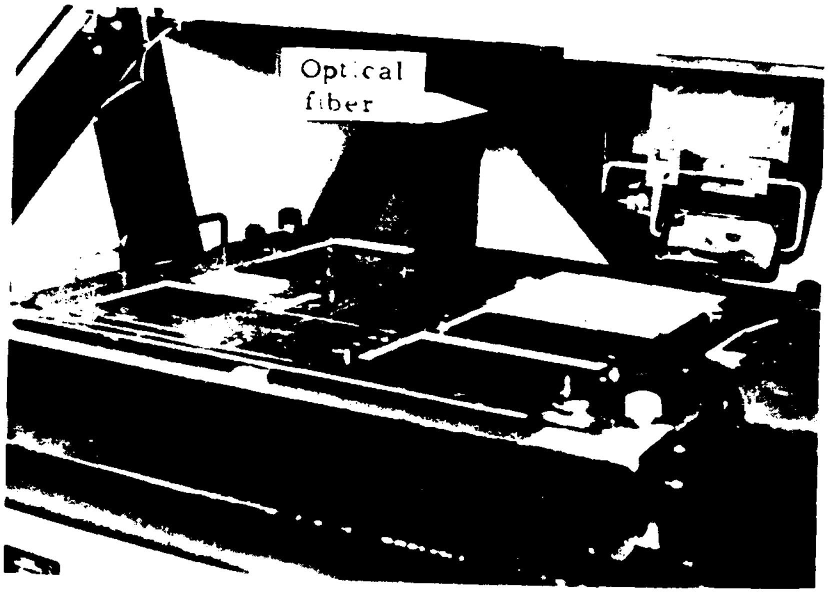
The system is shown in Figures 1 and 2 and will be described in some detail after we discuss the basic principles of its operation.

THE LASER/THERMAL INSPECTION CONCEPT

The operation of Laser/INSPECT relies upon what we call "laser/thermal testing" wherein a heat pulse which is applied to the surface of a test object can reveal certain information about the surface of the material as well as about its internal features. The information is contained in the warming and cooling characteristics which in turn are revealed by one's simultaneously monitoring the surface, during and after heating, with an infrared detection system. The method is applicable to the testing of a variety of metallic and other structures, but here we shall describe its use only in connection with solder joints.

Figure 3 illustrates a typical such case involving lap joints at flat-pack IC's. The lead and pad thicknesses are exaggerated for clarity. The upper sketch represents a normal joint and the solid black area in the lower sketch signifies a void.

By use of a focused laser beam, an intense, short-duration heat pulse is applied to the upper surface of the joint. The heat flows freely into the metallic interior parts provided that they are in thermal contact with the surface. The temperature rise at the surface is monitored by the infrared



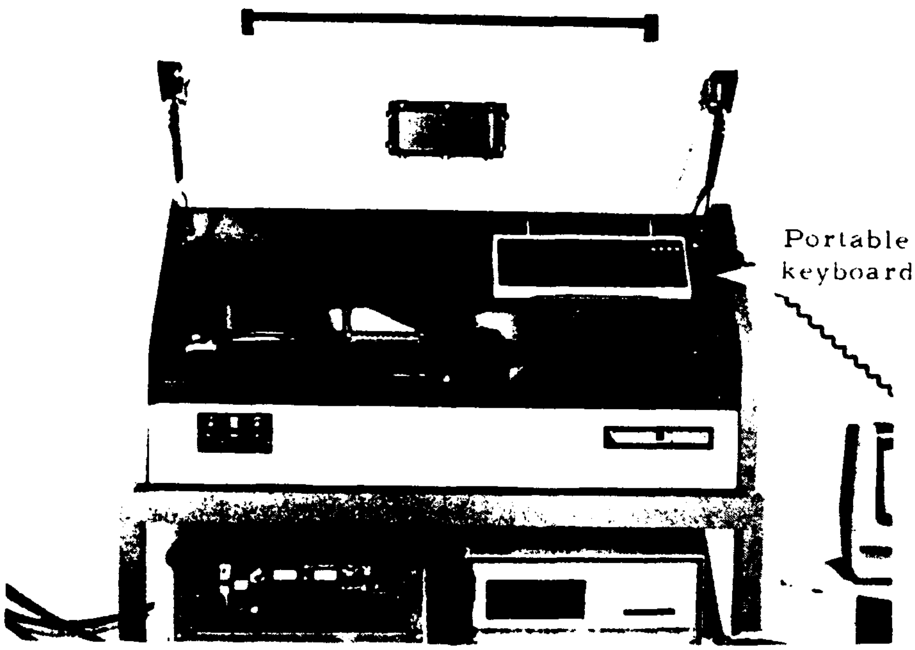


Figure 2. Interior views of Li/6000 inspection cabinet. Upper photo shows board-mounting fixture on XY table.

Figure 1. The Model Li/6000 Laser/INSPECT.

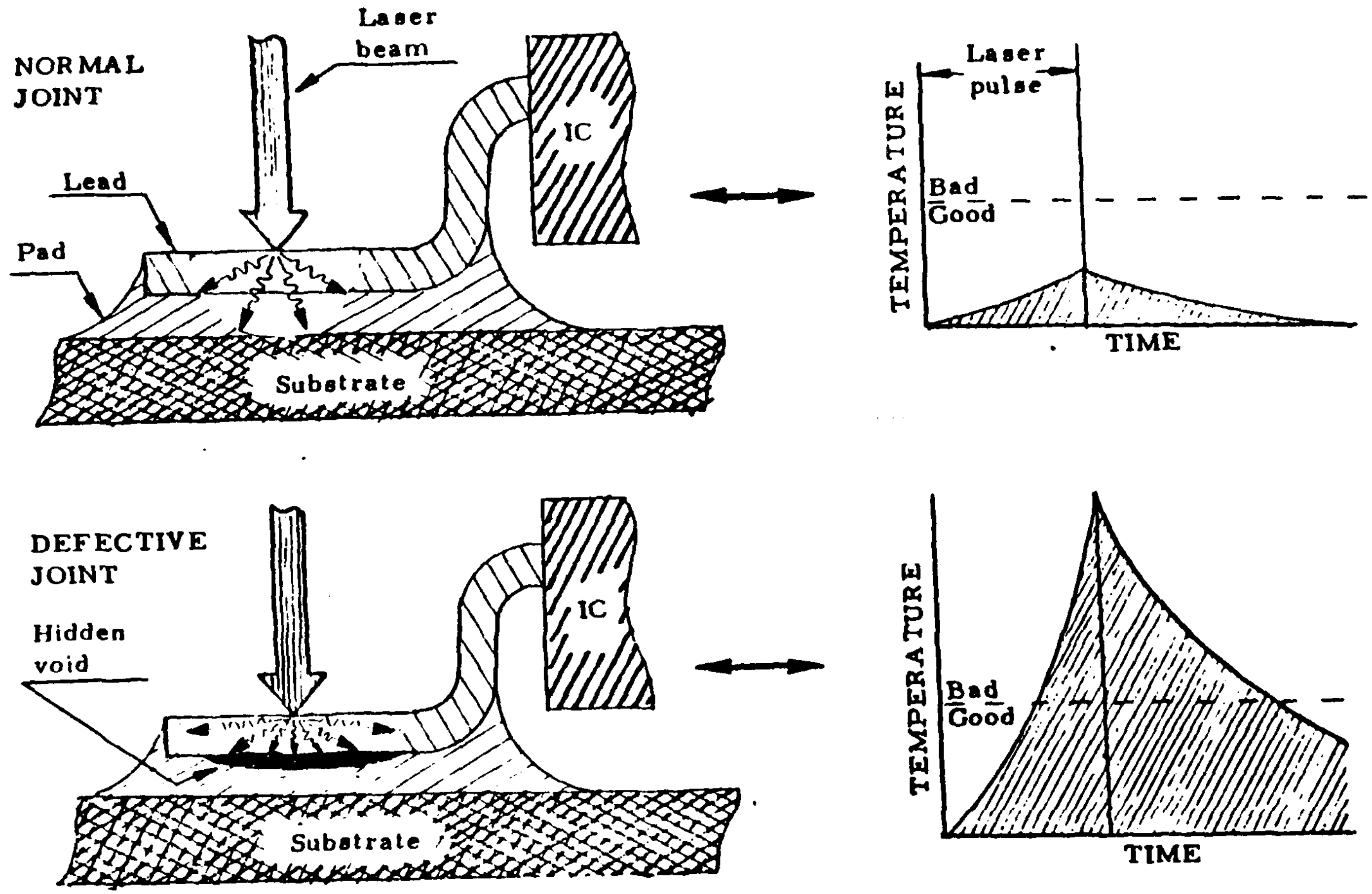


Figure 3. Behavior of normal and defective lap joints during laser/thermal testing.

system, which also monitors the cooling process. A typical heating/cooling curve, or "thermal signature", is sketched at the upper right of the figure.

In the lower lefthand drawing, the injected heat becomes concentrated in the partly detached lead because it finds less of an escape path. The result is a higher surface-temperature rise than for a good joint, as shown at the lower right. The difference in the heights of the curves can be easily recognized by a computer and the faulty joint can be flagged as defective.

This is one example of the many types of defect which can be found by the laser/thermal method with the use of thermal signatures. In Figure 4 we show a family of such signatures representing groups of solder joints which have particular properties. The signatures for normal joints fall within a well-defined band, there being some variability due to expected differences in surface texture, solder mass, heat-sinking, and so forth. The cross-hatched regions, by comparison, show that the curves for various defects will fall either above or below the normal ones.

The matter of where a given thermal signature will fall depends principally upon two features of the solder joint: its surface condition and its internal structure.

Regarding the former, it is a feature of a clean, smooth, shiny solder surface that it is a good reflector for the 1.06-micrometer (μm) laser radiation which falls upon it. Most of the power is reflected away, with a small amount remaining and warming the surface. Hand in hand with being a good reflector (or poor absorber), such a surface is automatically a poor emitter, according to known physical laws. Therefore, the amount of thermal radiation which it emits upon becoming warmed is less than it would be if the surface were not clean and shiny.

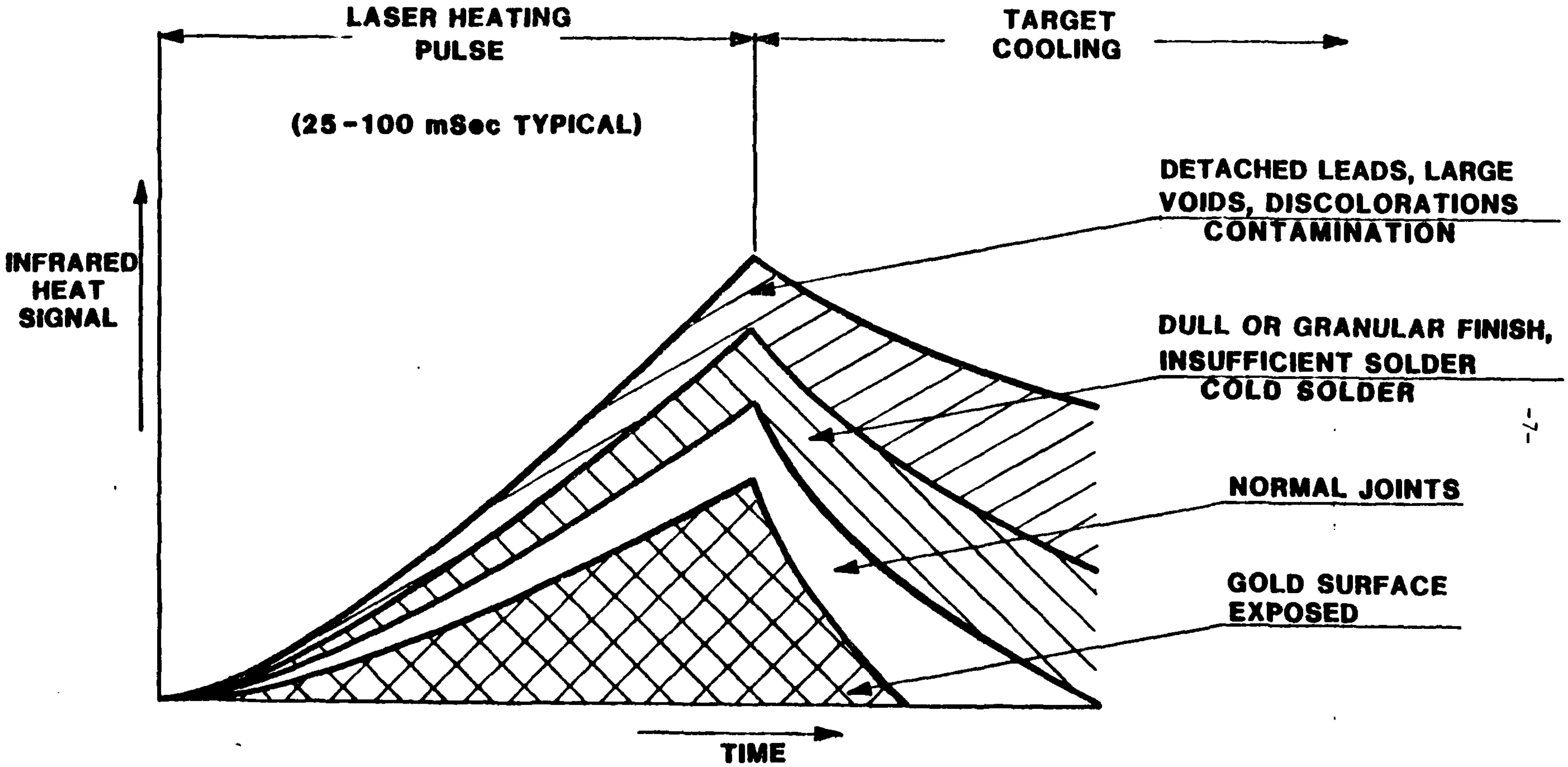


Figure 4. Infrared signatures of solder joints.

As a result, any surface contamination, discoloration, haze, roughness, pinholes or other deviation from the normal condition will cause not only an increase in the absorption of laser radiation, with consequent higher temperatures, but a proportionately greater increase in the amount of thermal emission which is received by the infrared detector, the latter increase being due to emissivity alone. The multiplicative effect of these separate phenomena emphasizes the differences in thermal signatures between a normal and a slightly abnormal surface.

In the special case of a shiny gold lead which had inadvertently not been covered with solder, this would have an even higher reflectivity (and lower emissivity) than clean solder, leading to a lower-than-normal thermal signature.

Once the laser-beam power has entered the surface and has been converted to heat, the energy tends to dissipate within the material, again according to physical law. One can think of the thermal energy as tending to find escape routes within the mass of the joint and its adjoining metallic parts. If it is successful, heat buildup near the surface is avoided and normal warming prevails; if not, higher-than-normal surface temperatures are seen by the detector.

Internal heat-escape from the surface is facilitated if more rather than less solder is present, or if the surface is thermally well connected to other metallic masses or "heat sinks", and if voids, inclusions or other thermal barriers do not impede the normal heat flow process.

The upper part of Figure 5 again portrays the good and the defective lap joints which have been shown in Figure 3, this time with more realistic dimensional scaling. The lower part of Figure 5 shows two other typical lap joint defects, comprising a lifted toe and a cracked heel. In both cases, the heat flow paths to the pad are less complete than for the normal lap joint.

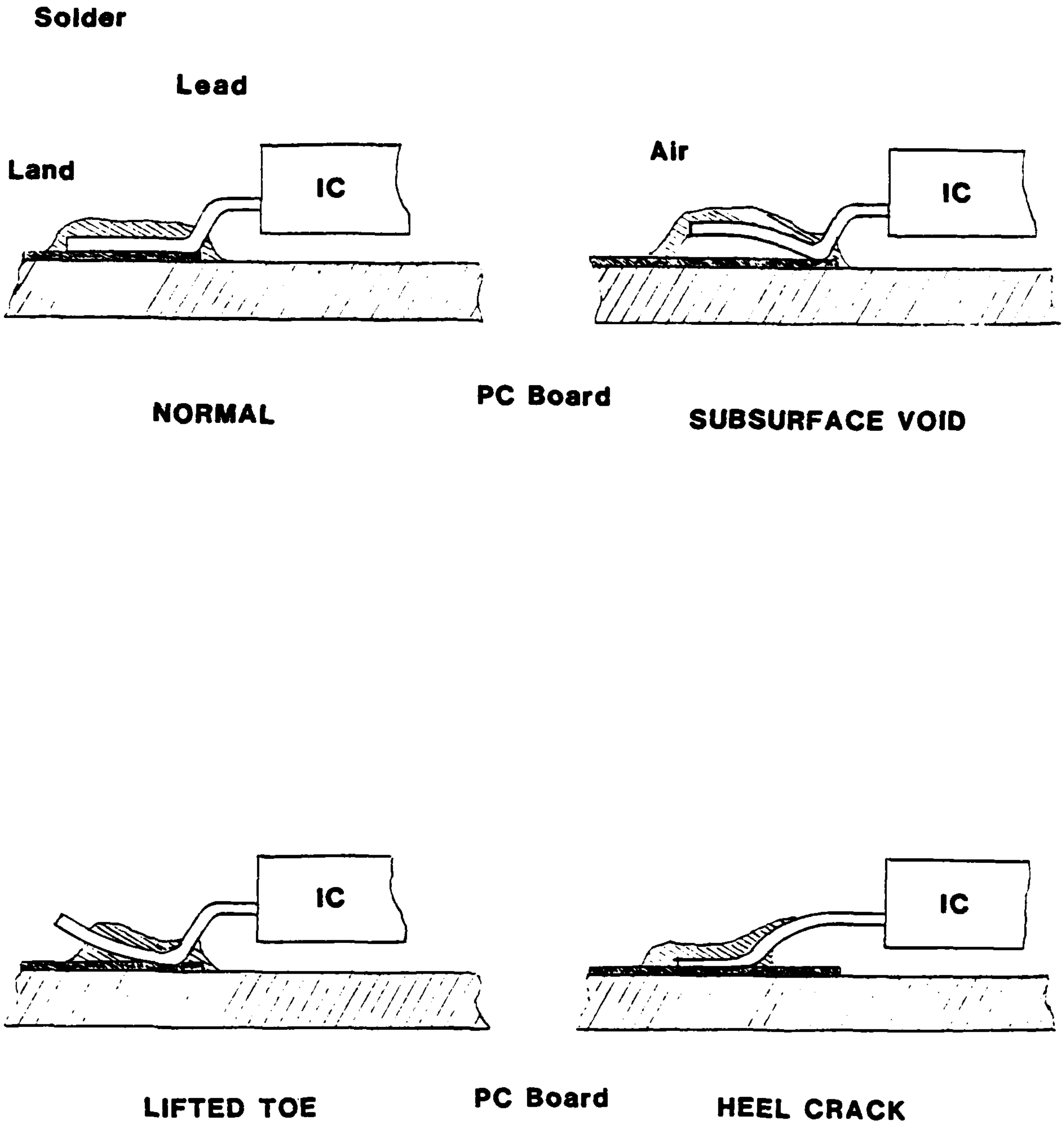


Figure 5. Examples of lap joints.
(Lap joints are tested from the component side.)

Figure 6 illustrates a normal feed-through or "pin-in-hole" joint by comparison with three of several common defects in such joints. In the upper righthand and lower lefthand figures, the reduced thermal mass in contact with the laser-heated surface (which faces downward in the sketch) will provide higher thermal signatures, as expected. At the lower right, the cavity facing the laser beam will further enhance the temperature rise by acting both as a light-trap for the laser beam and as a more efficient emitter for the thermal radiation.

Actual thermal signatures, recorded from oscilloscope traces, are presented in Figures 7 and 8. In the former is a photomicrograph of two identical-appearing feed-through joints. Sample A is typical of a normal-appearing joint which actually contains a large subsurface void which is revealed by laser/thermal testing, as in the oscillogram below, and whose presence is then verified by sectioning.

Figure 8 includes a photograph of a defective lap joint which is adjoined by two normal neighbors. The defects take the form of a lifted toe and a cracked heel. One laser-beam exposure each at the toe, center and heel of this joint resulted in the characteristic pattern shown in the Figure 8 oscillogram.

Figure 9 shows metallurgical cross sections of three feed-through joints, two of which contain internal voids. The thermal signatures shown below the respective photographs were plotted from actual Laser/INSPECT data taken on these joints. The photographs are oriented with the component side upward. The solder side, from which the inspection was carried out, is at the bottom. The correlation between the voids and the higher-than-normal thermal signatures is clearly seen.

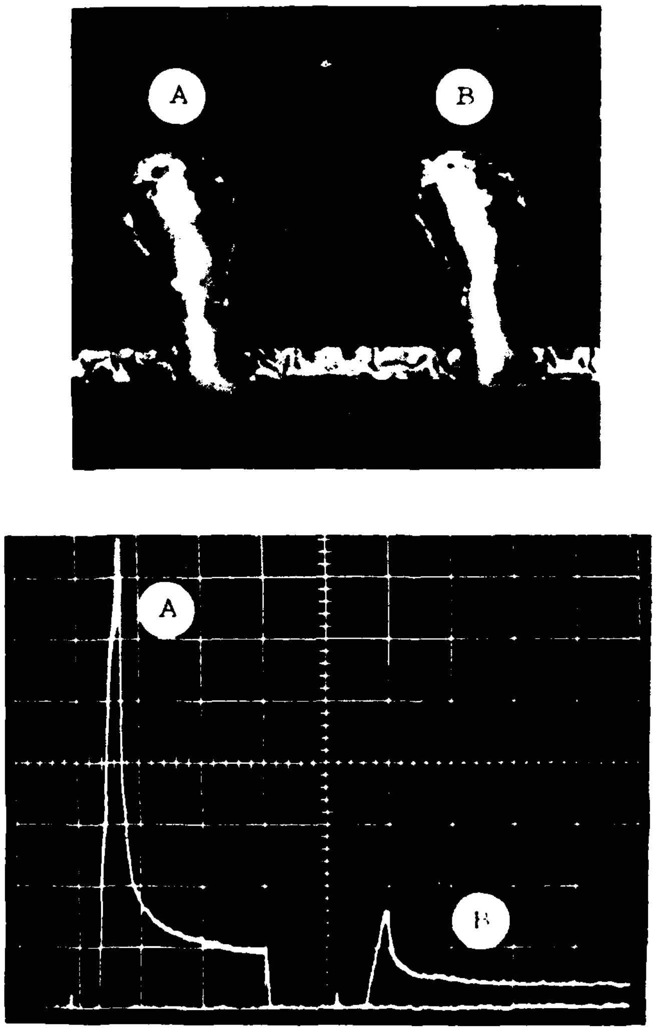


Figure 7. Detection of a hidden defect in a feed-through joint.

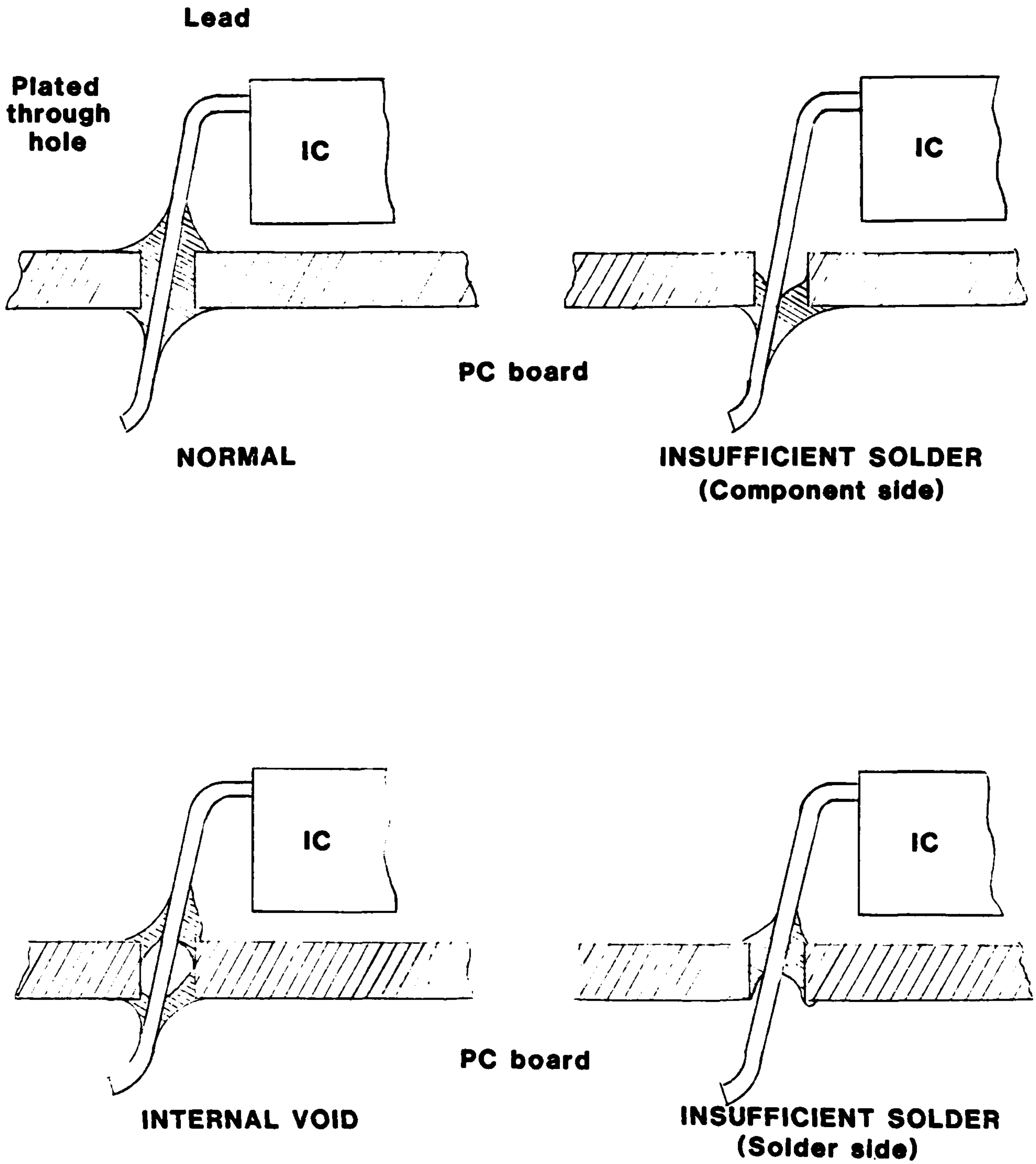


Figure 6. Examples of feed-through joints.
(Feed-through joints are tested from the solder side.)

The cross sections of Figure 9 were prepared, along with a great many others, by M. Martyn of the Naval Weapons Center at China Lake while he was with the Soldering Technology Branch, Product Assurance Division.

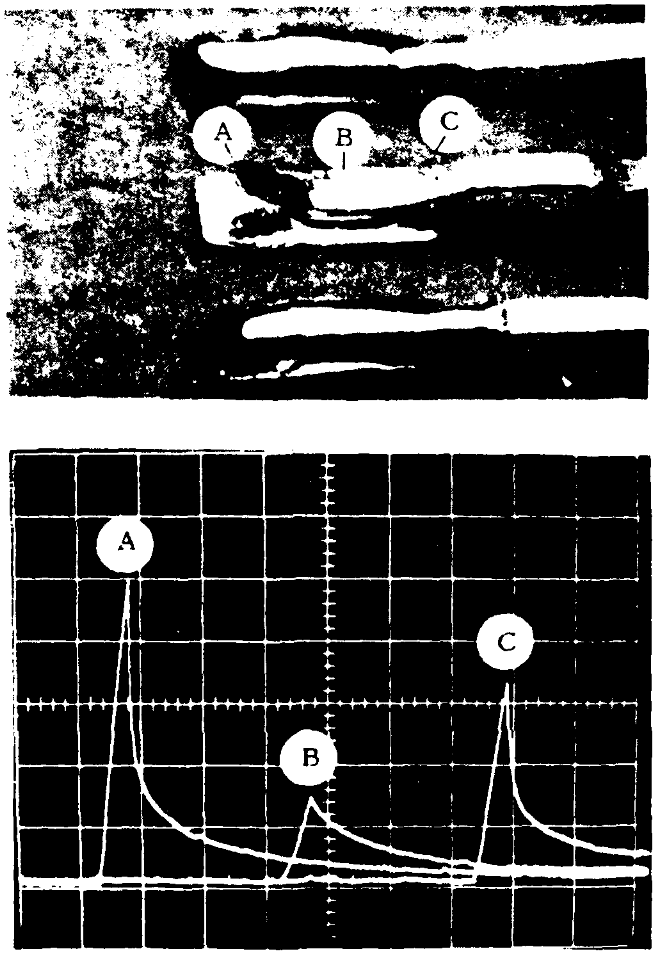


Figure 8. Detection of lap-joint defects.

DESCRIPTION OF LASER/INSPECT

The principal parts of the Laser/INSPECT system are:

- An aiming and heat-injection subsystem;
- An infrared-detection subsystem;
- An XY positioning table;
- A computer.

The functions of the computer are:

- To allow the position-programming of the solder joints which are to be tested on a given board (typically, the board is from a family of identical boards to be tested);
- To store the individual thermal signatures of the joints on a known good board, to serve as reference for the test boards;
- To move the test joints into the target position sequentially and to fire the laser shutter for a controlled duration;
- To monitor and record the infrared detector output for each solder joint and to compare it with its counterpart on the reference board;
- To determine, on the basis of pre-established limits, whether or not each thermal signature is within the acceptance band, and to output this information;
- And to perform subsequent statistical processing of test-information derived from each board for purposes of manufacturing-trend analysis.

We shall describe the subsystems of Laser/INSPECT in some detail. The reader is referred to Figure 10 for the discussion.

The Aiming and Heat-injection Subsystem

Heating is provided by the focused radiation beam from a 30-watt neodymium-doped yttrium-aluminum-garnet (Nd:YAG) laser operated in a continuous (rather than pulsed) mode and with a multimode beam spatial structure. The radiation

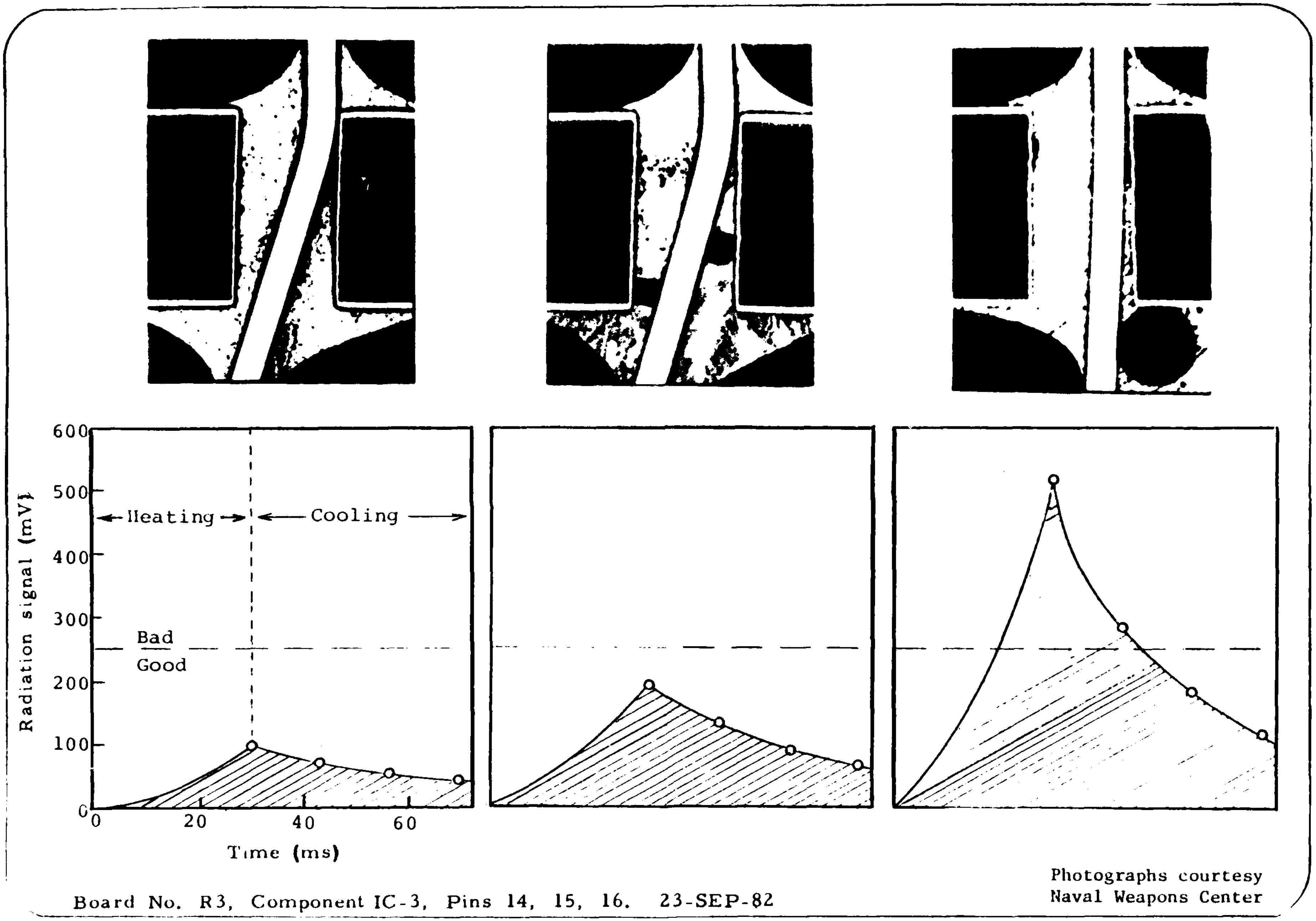


Figure 9. Laser/INSPECT detection of internal voids.

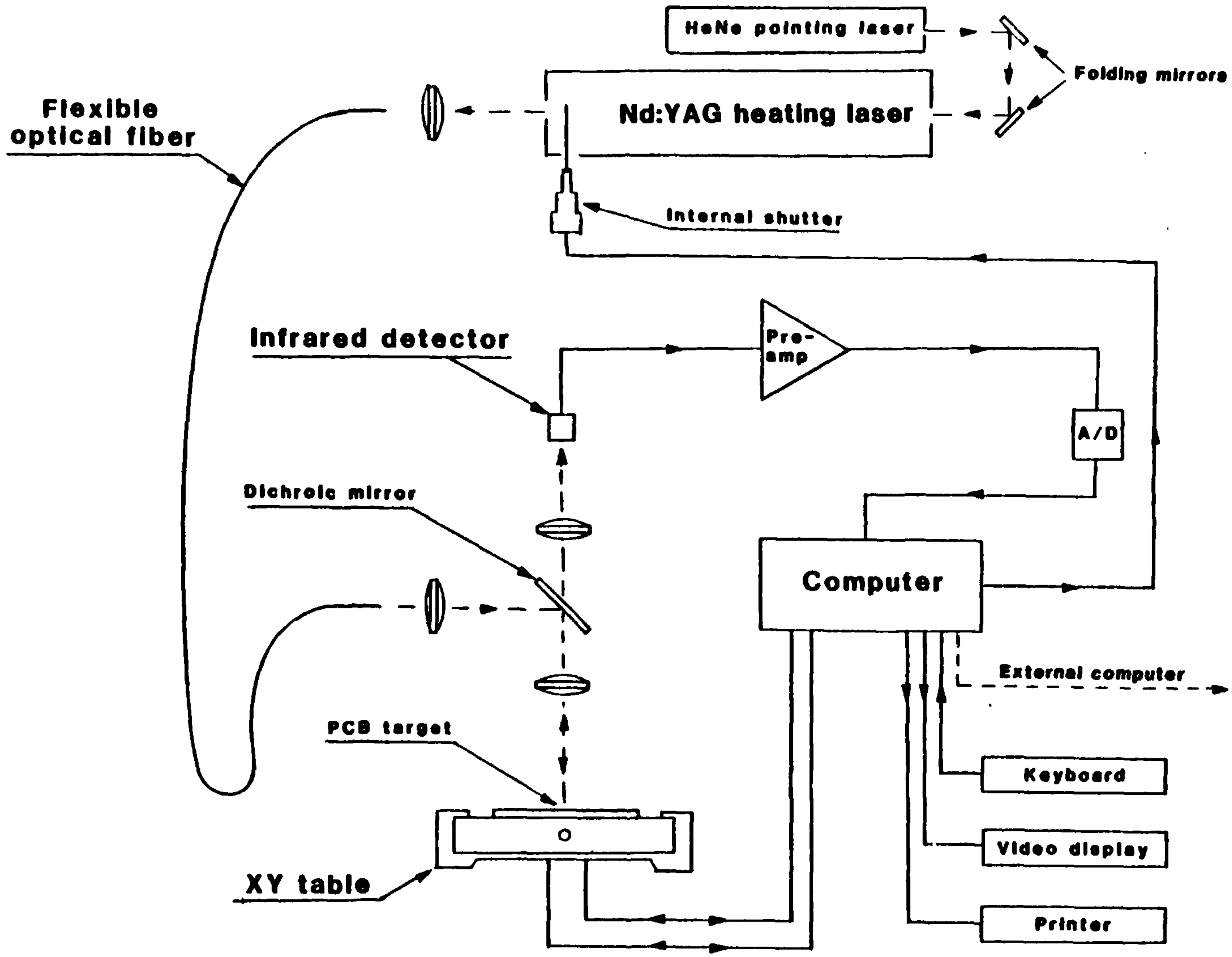


Figure 10. Laser/INSPECT system diagram.

wavelength is 1.06 μm and, as with any "YAG" laser, could cause eye injury or skin burns if used improperly. Government-prescribed protective measures are therefore incorporated into Laser/INSPECT, by use of safety interlocks, to avoid any possible hazards.

As an aid in the manual programming of solder-joint positions, a small amount of visible light is added to the YAG laser beam. This is done by injecting red light from a half-milliwatt helium-neon (HeNe) laser, operated at 0.6328 μm, into the rear aperture of the YAG laser. The HeNe beam is carefully aligned to ensure coincidence with the YAG beam.

Both beams emerge from the output aperture of the YAG laser and are focused onto the input aperture of a flexible, high-purity glass fiber having a 0.024-inch diameter. One purpose of the fiber is to homogenize the laser beams, by means of random, multiple internal reflections, so that the power density is uniformly distributed over their cross sections. If this were not done, there would be "mode structure" (a non-uniform interference pattern common to all laser beams) in the focused spot falling on the target.

A second purpose of the fiber is to provide mechanical isolation between the lasers and the positioning table; otherwise, vibrations due to the start/stop nature of the table motion would cause jitter in the optical beams.

Upon leaving the output aperture of the fiber, the laser beams diverge until they are intercepted and rendered nearly parallel by a "fiber-output" lens. They then impinge upon a "dichroic beamsplitter" mounted at a 45-degree angle to the beam. This element has the special property of being a mirror at the laser-beam wavelengths while serving as a window for the greater, thermal-infrared wavelengths monitored by the detector. The laser beams are thus directed downward toward the target and are focused onto it by an infrared-transmitting lens.

Exposure durations are computer-controlled by use of a light-weight, fast-acting shutter inside the YAG-laser cavity. Being internal, the shutter actually halts the lasing action when it is closed; if mounted externally, the shutter would have to deflect or to dissipate the intense beam radiation when closed, thus complicating the system design.

In the target region, the spot diameter is typically 0.020 to 0.030 inch, being adjustable to accommodate various solder-joint configurations; for leadless-chip-carrier (LCC) joints, it is made smaller. The YAG beam power is adjustable as well; typically not more than ten watts of power are required at the target for effective testing. Exposure durations of 30 milliseconds are standard. One might presume that shorter exposure durations at higher beam powers would increase the inspection rate. If this were done, however, there would not be sufficient time for heat-penetration into the solder joint for its internal properties to be revealed.

<u>The Infrared-detection Subsystem</u>

The sensitive element in this system is a 0.004-inch-square film of indium antimonide (InSb) which is cryogenically cooled to 77 degrees kelvin and which responds largely to wavelengths in the 2.5 to 6 micrometer region. With a suitable optical system, it can detect changes in target temperature as small as one-twentieth of a centigrade degree.

During the laser-beam exposure, a typical target becomes warmed to no more than 50 centigrade degrees above the surround, depending upon its surface condition. This is safely below the melting or "reflow" temperature for solder but is sufficient to cause the solder surface to emit long-wave infrared radiation which can be detected. The thermal radiation which is intercepted by the lower lens in Figure 10 is rendered somewhat parallel and passes through the

beamsplitter to an upper infrared-transmitting lens where it is focused onto the detector surface. The electrical output signal of the detector is amplified and proceeds to an analog-to-digital (A/D) converter where it is processed for transfer to the computer.

The inherent response time of the cooled detector is less than a microsecond. Its response speed is therefore more than adequate to follow the warmup and cooldown processes which endure for many milliseconds.

The detector is inherently somewhat sensitive to the shorter wavelength power radiated by the YAG laser. Because directly reflected YAG radiation would conflict with the thermal radiation arriving at the detector, the latter is equipped with a short-wavelength blocking filter, which is essentially opaque at 1.06 μm.

The detection-system electronics are designed such as to render the detector insensitive to ambient-temperature drift at the PC board. Just prior to each laser-beam exposure, the detector reading of the "room temperature" target (regardless of its value) is set to "zero". Subsequent thermal radiation readings are thus referred to this value so that the actual temperature increase due to the exposure is recorded, instead of absolute values.

The XY Positioning Table

The table is of special design in order to achieve an otherwise unobtainable combination of light weight, high speed, and precision positioning. A 16- by 18-inch inspection area is specified, with a positioning resolution of 0.001 inch and with a positioning repeatability of ±0.0001 inch. The X and Y stages move on linear bearings and are driven by precision lead screws connected to DC torque motors. Optical shaft-angle encoders within the motors provide closed-loop operation. This ensures more dependable performance than the often-used open loop operation.

The table is configured so as to receive an aluminum mounting plate (or "fixture") upon which are mounted the boards to be tested. For each size and shape of board, an aperture is milled in the mounting plate, with shoulders being provided upon which the board rests. Dowel pins are provided in the shoulders for repeatable positioning of the boards of a given type, making use of the tooling holes in the board. Depending upon the board size, several apertures can be prepared in each mounting plate.

The latter is in turn precisely mounted on the frame of the XY table, again being located by use of dowel pins and being clamped in place after mounting.

The Computer

Figure 11 shows the computer hardware as related to the rest of the system.

The electronics system uses a Digital Equipment Corporation single-board computer, Model LSI-11/23, with 128 kilobytes of RAM and a 4-port RS232 communications board. The information storage system is a Data Systems Design DSD 880 10-Mbyte Winchester/512 kbyte floppy storage system. The computer system and interfacing boards are housed within the CRT terminal, which is a DEC VT103 chassis. A DEC LA-120-RA line printer generates hard copies of the outputted data and a port in the VT103 is available for connection to an external computer.

Software included with the system was developed under "FORTRAN" and "MACRO-11" languages and allows for the programming of a virtually unlimited number of solder joints on PC boards up to 16 by 18 inches in size. Other software programs manage the individual reference signatures of the standard solder joints used for comparison. They also process the thermal data statistically for trend analysis in the case of subtle changes occurring in the manufacturing process over a period of time.

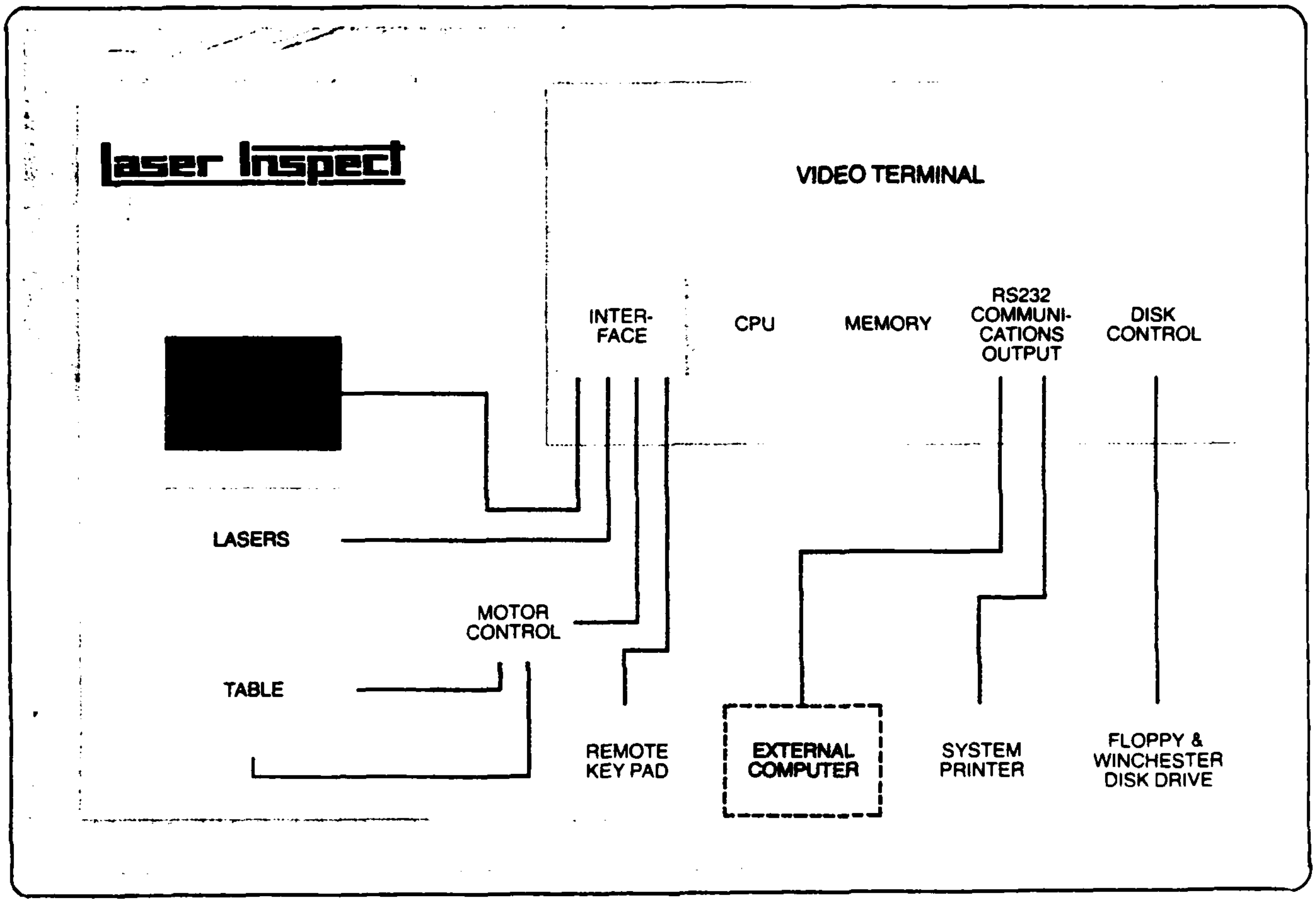


Figure 11. Electronics block diagram of the Li/6000.

Another software feature is included which is designed to prevent laser-beam damage to any non-metallic target that is inadvertently brought into the target zone through either an operator- or a system-error. The infrared detector signal is continuously monitored for any evidence of runaway heating such as might precede an incipient burn on a combustible material (substrate, component, etc.). Within milliseconds of any such evidence being found, the laser shutter is automatically and prematurely closed and the operator is notified of this on the printout. The system then clears itself and proceeds to the next programmed target.

As will be seen in later pages, the computer provides a complete printed record of all solder joints tested, including their designations, XY-locations, radiation-signal values, and whether or not they are defective.

USING THE LASER/INSPECT

Fixturing and Programming

A blank mounting plate (fixture) and hold-down clamps for the PC boards are provided with Laser/INSPECT; additional ones are available separately. Instructions are provided as to how cutouts are to be specified for the test boards. Typically, several identical boards will be mounted on the fixture together, depending upon their sizes. An illustrative arrangement is shown in Figure 12. Alternatively, boards of diverse configurations may be mounted on the same plate.

Dowel pins to be installed in the fixture will ensure repeatable positioning of successive boards, assuming that these are provided with tooling holes from which the locations of all solder joints on the board are known. It is recommended that the solder-joint locations with respect to the tooling holes be held to within ±0.003" tolerances.

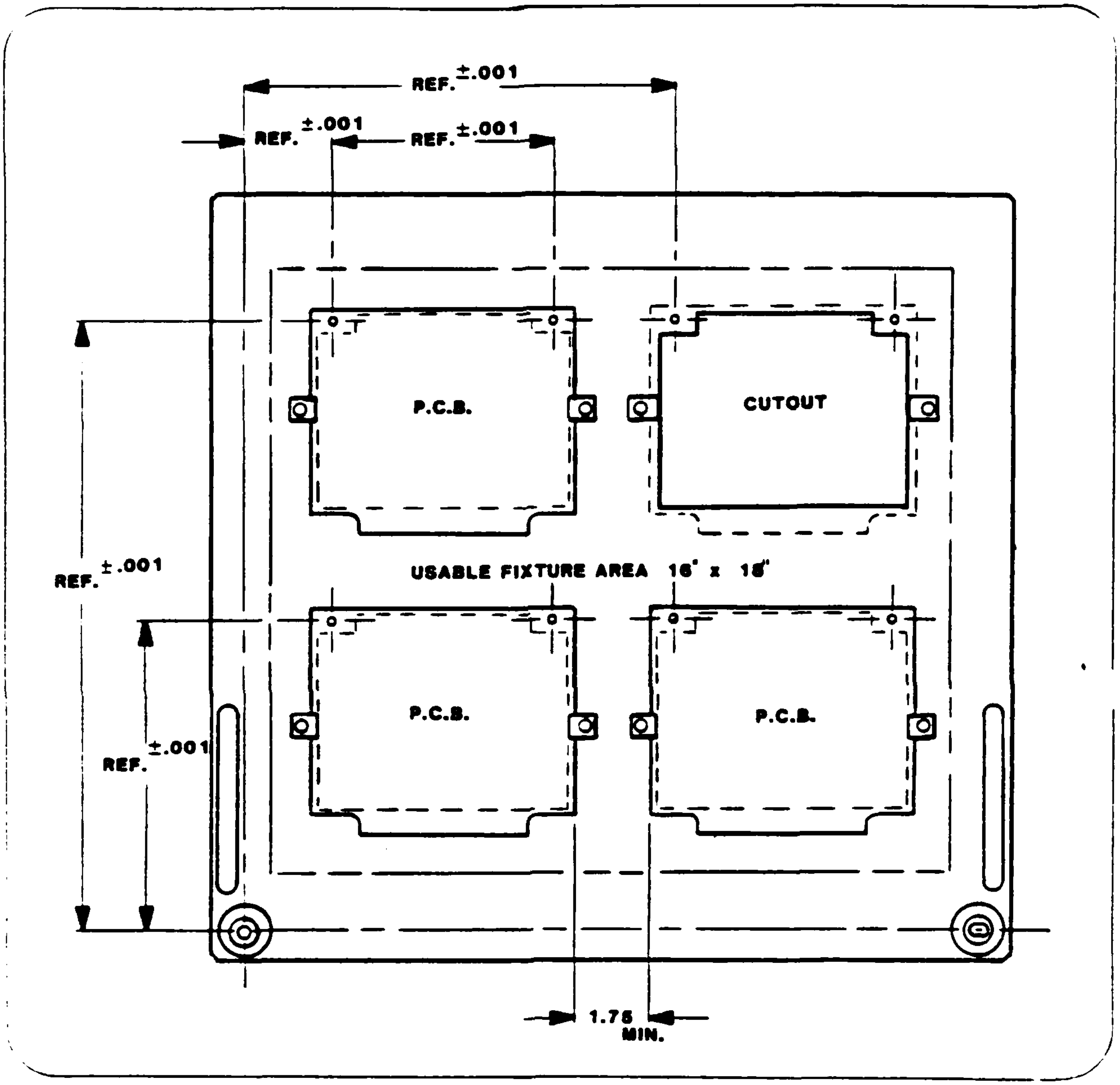


Figure 12. A typical arrangement of PC boards on a Laser/INSPECT fixture, showing an unloaded cutout at the upper right.

The boards are to be mounted solder-side upward in the fixture. Above the boards, there is a 1.38" clearance to the injection head for any large components which may be located on the solder side. Components on the other side of the board may be up to two inches in height. Up to ±0.10" of bowing is allowable in each board.

As an option, provision can be made for the automatic programming of solder-joint locations by use of numerical data used earlier for hole drilling. Alternatively, manual programming may be used, either by keyboard entry of available coordinate data in tabular form or by visually locating each target with the aid of the pointing laser. The latter is carried out by "jogging" the table, by use of the keyboard, so that each target, in succession, is brought to the target position where it is seen to be centered in the bright-red laser spot; its position is them automatically entered by keyboard. For components having a regular solder-joint configuration (a 16-pin DIP, for example), only two diagonally opposite pin locations need be entered (Pins 1 and 9, in this case). A separate sub-routine in the computer will complete the programming for the DIP (or flat-pack IC, etc.) provided that its orientation and number of pins are entered. By knowing the numbers and locations of the two key pins which are entered, the computer is able to deduce whether the pins are on 0.10" centers, as on DIP's, or on 0.05" centers, as on flat-pack IC's, or at some other spacing. For multiple, identical boards appearing on one fixture, only one of these need by programmed; keyboard-manipulation of the program can then replicate it at the other locations.

Manual programming is most accurate when carried out on a blank rather than a completed circuit board so that any solder-surface irregularities will not introduce slight position errors during visual targeting. The centering of empty plated-through-holes is marked by the disappearance of the pointing-laser spot into the hole.

A dry run of the system, with the YAG laser off and by use of visual observation, will verify the absence of any programming errors.

Profiling

Laser/INSPECT is a self-teaching system which needs only to be "shown" one or more circuit boards which are known to be acceptable. By testing each joint on every reference board, it memorizes the thermal signature for each joint and also derives statistical information about the normal spread of data for the same joint on different boards. Thereafter, for each test joint, the system can make a judgment as to whether the thermal values for the joint are within or outside of an acceptance band.

Various users will choose different procedures in setting up the acceptance band. A minimum of three reference boards is suggested, although more meaningful statistical data will result if more reference boards are used. If all solder joints on each board are identical in structure (size, shape, amount of heat sinking, etc.), their distribution of peak thermal values will fall closely about the average value. This value may then be multiplied by some small integer, such as two or three, in order to establish an upper bound to the acceptance band. Dividing the value by the same or a different integer can establish the lower bound. Alternatively, use may be made of the standard deviation of the peak-value distribution and a pair of multiplying factors.

If the joints are of basically different types so that their normal peak thermal values fall into separate groups, the values may be operated on differently so that each type of solder joint will have its own acceptance band.

The wider or narrower the user chooses to make the band, the less or the more critical the system will be in judging solder joint quality.

The standard system procedure uses peak thermal values to make go/no-go decisions. As we shall discuss shortly, additional thermal data are available in the form of cooling-rate data. These are useful in distinguishing between certain types of defects as well as between real defects and false ones due to the chance burnoff of debris or other contamination which sometimes occurs at a joint. Procedures are available in which the computer may be used to aid in distinguishing these cases by use of the cooling-rate data.

Testing of Production Boards

The profiling and inspecting of boards are preceded by a turn-on procedure in which electrical power is provided to the computer, the lasers, the table motors, etc., cooling water is applied to the YAG laser, and liquid nitrogen is applied to the IR detector. A five-minute waiting period is recommended, for system stabilization.

The test boards are to be individually numbered and are mounted on the fixture plate. The cabinet safety door is then closed and locked via a key switch in order to permit YAG-laser operation. A few instructions to the computer are all that is needed to start the program. The instructions include the identification number of each board being inspected so that the data for each board may be properly identified in the printouts and can be recalled later if needed.

A final instruction is entered by depressing a "SCAN" key which starts the automatic inspection cycle. Each solder joint is then brought to the target position, the laser-beam exposure is made, and the target is held in position while the peak thermal value and three cooldown readings are taken. The next joint is then moved into position and the process repeated. After all boards on the fixture have been tested, they are replaced by the next batch and the process is started again.

While the data are being taken, the line printer rapidly prints the inspection data for each solder joint, if desired, or only for those found to be defective.

A description of a typical thermal-data printout format follows.

The Radiation Data Printout Format

An example of a printout, with each line of data representing a solder joint, is given in Table 1. This is the first page, only, of a full printout for a board which may cover a great many pages, depending upon the number of joints.

Across the top line we have:

The date of the test

The "Laser/INSPECT" identification

The upper flagging level of 249, in this case (peak radiation values higher than this will be flagged)

The lower flagging level of 11

The file name (Board KA1) for later recall of data from the file

The page-number sequence for the printout sheets of each board.

The columns of data are organized as follows:

Component: An abbreviation identifying the component is entered in this column. "CA1", for example, may represent Capacitor No. 1.

Sequence No: The sequential order in which the components are tested. This is helpful for later directory look-up in order to find a certain component in a long printout.

Pin No: The pin of each component is identified by the computer according to standard notation.

X and Y Coordinates: Each pair locates a given solder joint, in units of thousandths of an inch, with respect to the common origin of coordinates.

P/Units: These are the peak thermal signals, in arbitrary radiation units related to the amplified detector signal in millivolts, which occur at the end of each laser-beam exposure. Their values are relative to the initial temperature

TABLE 1. A TYPICAL PRINTOUT OF RADIATION DATA.

DATE 10-AUG-82 Laser/Inspect Defects Above > 249 Defects Below > 11 File Name KA1 Page (1)

COMPONENT:	SEQ#:	PIN-NO#	X-COORDS	Y-COORDS	P/UNITS	M/UNITS	L/UNITS	F/UNITS	FLAGS
CA1	1	1	2263	2548	615	413	285	231	<-DEFECT
CA1	1	2	2263	2357	239	119	98	76	
U1	2	1	2386	2262	45	26	22	22	
U1	2	2	2493	2262	69	49	44	42	
U1	2	3	2596	2262	48	33	29	26	
U1	2	4	2696	2262	235	94	68	58	
U1	2	5	2696	1962	42	26	24	18	
U1	2	6	2594	1962	44	24	21	18	
U1	2	7	2492	1962	73	40	32	26	
U1	2	8	2389	1962	44	26	22	21	
C3	3	1	1939	1937	24	22	18	16	
C3	3	2	2138	1937	34	16	13	12	
CR5	4	1	1899	1803	36	20	18	16	
CR5	4	2	2241	1803	50	36	31	28	
R7	5	1	2759	1847	28	18	18	16	
R7	5	2	2404	1847	33	19	17	17	
Q5	6	1	2859	2081	38	24	22	21	
Q5	6	2	2859	1988	36	23	22	19	
Q5	6	3	2859	1884	51	26	25	22	
C4	7	1	2991	2358	36	16	10	14	
C4	7	2	2991	2161	27	16	15	13	
CA2	8	1	3102	2163	49	26	21	19	
CA2	8	2	3102	2015	143	65	54	51	
CA3	9	1	3258	1917	4095	319	234	207	<-DEFECT
CA3	9	2	3464	1915	71	42	35	31	
CA4	10	1	3249	2029	4095	307	184	137	<-DEFECT
CA4	10	2	3461	2032	60	37	31	27	
CA5	11	1	3234	2182	1360	1088	908	733	<-DEFECT
CA5	11	2	3414	2187	68	39	31	27	
CA6	12	1	3233	2347	1743	1521	1108	895	<-DEFECT
CA6	12	2	3416	2347	84	47	35	30	

of the solder joint which is taken as "zero" by use of an auto-zero step at the start of each exposure.

M, L, and F/Units: These are three successive readings taken, generally, at 5-ms intervals during the cooldown period as an aid in distinguishing among certain types of defect.

Flags: The word "Defect" is printed in this column whenever the P/Units value is above the upper flagging level or below the lower one.

In the rare instance in which a bit of foreign matter on a joint causes activation of the damage-prevention circuit, thus aborting the measurement, a row of special symbols (such as "-1") appears in the four radiation data columns.

In this example, we note five P/Unit values which exceeded 249. The two highest values are at the limit of the radiation signal scale which was in use during these tests.

In these particular tests, a single acceptance band applied uniformly to all joints being tested.

Statistical Processing of the Radiation Data

For trend analysis, solder-joint quality may be compared board by board or batch by batch if the peak radiation signals for each board are tabulated and/or graphically displayed in the form of a frequency-of-occurrence distribution for each possible radiation value.

Table 2 shows such a tabulation for 846 solder joints on a given board. Only the radiation signal range from 1 through 200 is represented in the columns of data. In the row of data below the columns, we note that 23 solder joints yielded the peak radiation value of 51. The average for the range and the standard deviation are given. Those points within the 1-to-200 range comprised 829 or 97.99" of the 846 total. In the bottom row are shown the ranges in which the 17 out-of-range points fell.

TABLE 2. FREQUENCY DISTRIBUTION OF PEAK RADIATION SIGNALS FOR A PARTICULAR BOARD HAVING 846 SOLDER JOINTS.

UNIT/VALUE	FREQUENCY	UNIT/VALUE	FREQUENCY	UNIT/VALUE	FREQUENCY	UNIT/VALUE	FREQUENCY	UNIT/VALUE	FREQUENCY
1	0	41	19	81	5	121	0	161	1
2	0	42	19	82	10	122	2	162	0
3	0	43	15	83	4	123	0	163	0
4	0	44	8	84	3	124	1	164	0
5	0	45	12	85	5	125	0	165	0
6	0	46	14	86	9	126	0	166	0
7	0	47	18	87	6	127	0	167	0
8	0	48	20	88	3	128	1	168	0
9	0	49	19	89	2	129	0	169	0
10	0	50	15	90	7	130	0	170	0
11	0	51	23	91	6	131	2	171	0
12	0	52	10	92	7	132	0	172	0
13	0	53	16	93	2	133	0	173	0
14	0	54	17	94	3	134	1	174	0
15	0	55	21	95	2	135	1	175	0
16	0	56	22	96	2	136	0	176	1
17	0	57	15	97	2	137	0	177	0
18	0	58	14	98	2	138	1	178	0
19	1	59	21	99	2	139	1	179	1
20	0	60	7	100	3	140	0	180	0
21	0	61	20	101	2	141	0	181	0
22	1	62	12	102	2	142	0	182	0
23	3	63	16	103	3	143	1	183	0
24	8	64	7	104	2	144	0	184	1
25	3	65	13	105	1	145	0	185	0
26	7	66	11	106	1	146	0	186	1
27	5	67	17	107	0	147	0	187	0
28	4	68	9	108	0	148	0	188	0
29	3	69	8	109	1	149	0	189	1
30	6	70	13	110	0	150	0	190	0
31	8	71	8	111	1	151	1	191	0
32	10	72	5	112	0	152	0	192	1
33	6	73	14	113	1	153	1	193	0
34	5	74	15	114	3	154	0	194	1
35	11	75	7	115	1	155	2	195	0
36	10	76	10	116	0	156	0	196	0
37	10	77	11	117	0	157	0	197	0
38	22	78	6	118	0	158	0	198	0
39	19	79	7	119	2	159	0	199	1
40	12	80	11	120	1	160	0	200	0

DATA POINTS	GREATEST FREQUENCY	UNIT VALUE	RANGE AVERAGE	STANDARD DEVIATION	POINTS INCLUDED	POINTS NOT IN RANGE	IN RANGE PERCENTAGE	RANGE SELECTED
846	23	51	60.830	25.34	829	17	97.99	200

1-50	51-100	101-200	201-500	501-1000	1001-2000	2001-3000	3001-4095	Unit/Values	Shutter
313	471	45	14	2	1	0	0	Frequency	30m.s.

The above data serve as a useful reference for board-to-board comparisons. Uniform, high-quality solder joints would be characterized as showing a tight cluster of low-valued radiation peaks, with a small standard deviation and with few out-of-range points. Board quality can be assessed "at a glance" if the frequency distribution data are plotted as a histogram, as shown in Table 3.

For purposes of the graph, the P/Units range has been extended to 250. At each ordinate is totaled the number of occurrences for that P/Unit value plus the four lower ones. Seven additional values are presented over those appearing in the table, so that 836 of the 846 points on the board are shown.

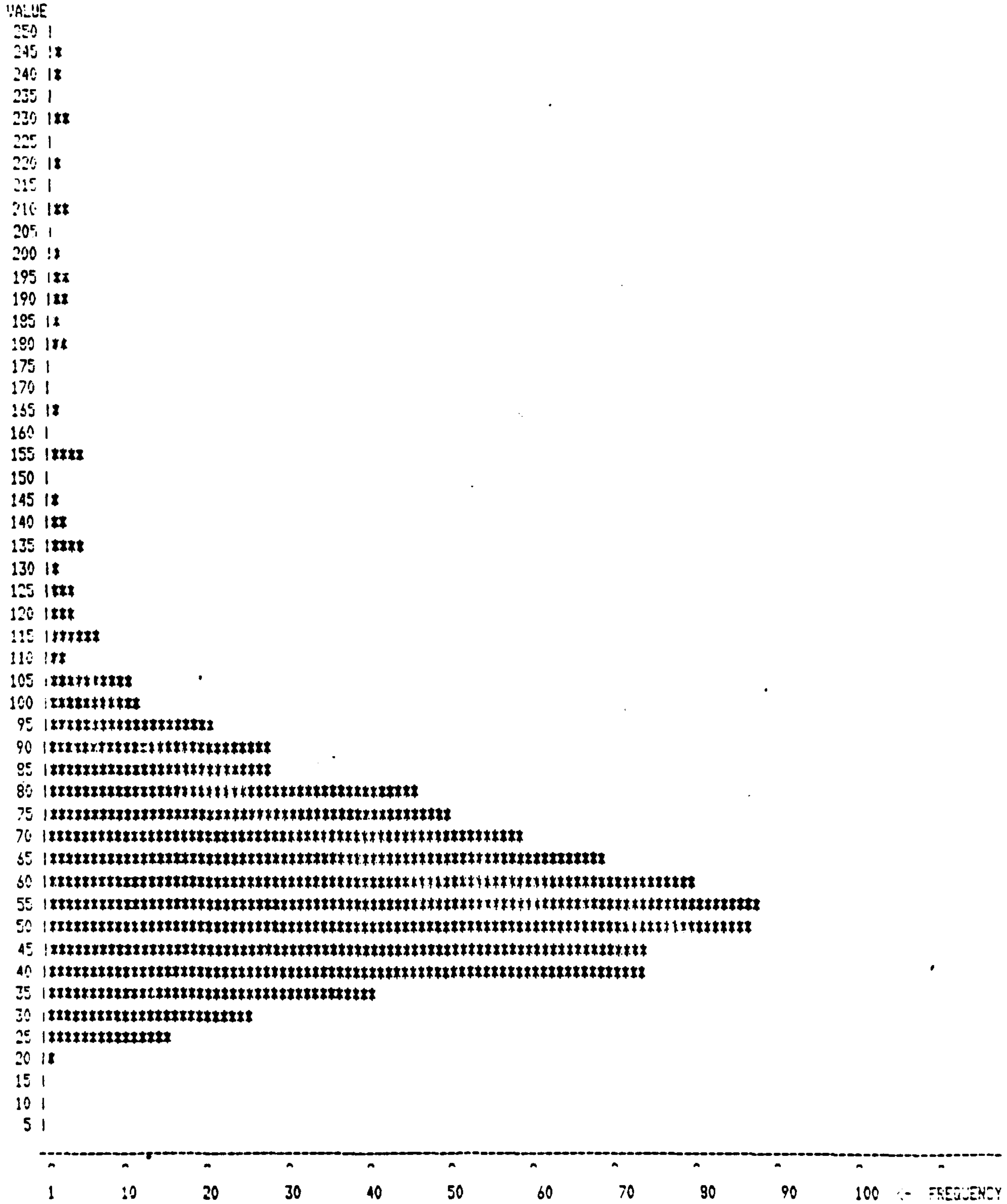
The characteristic shape of the curve, peaking at about 55, indicates relatively good quality for these solder joints, which were machine-soldered. An even higher quality example is seen in Table 4 and, for comparison purposes, the histogram of a hand-soldered board is shown in Table 5. In this case, the peak values fell more randomly and only 692 of the 896 data points on this board fell within the range plotted. In Table 4, nearly all the points fall at values of 105 or below.

The histograms shown so far are for boards having solder joints of the same type, notably feed-through joints of 0.050-inch diameters, all with about the same amount of heat-sinking. In cases where joints of more than one type appear on the same board, separate frequency distributions may appear in the histogram, causing it to show several cusps. An example appears in Table 6 in which less massive lap joints and more massive resistor-and-capacitor joints are represented along with the feed-through joints.

An interesting example of what can happen during board fabrication is represented by the histogram of Table 7. In the lower part is the tight cluster of data points indicative of good solder quality. Scattered in the upper region, however, is a group of points due to the poor solderability

TABLE 3. HISTOGRAM OF THE DATA IN TABLE 2.

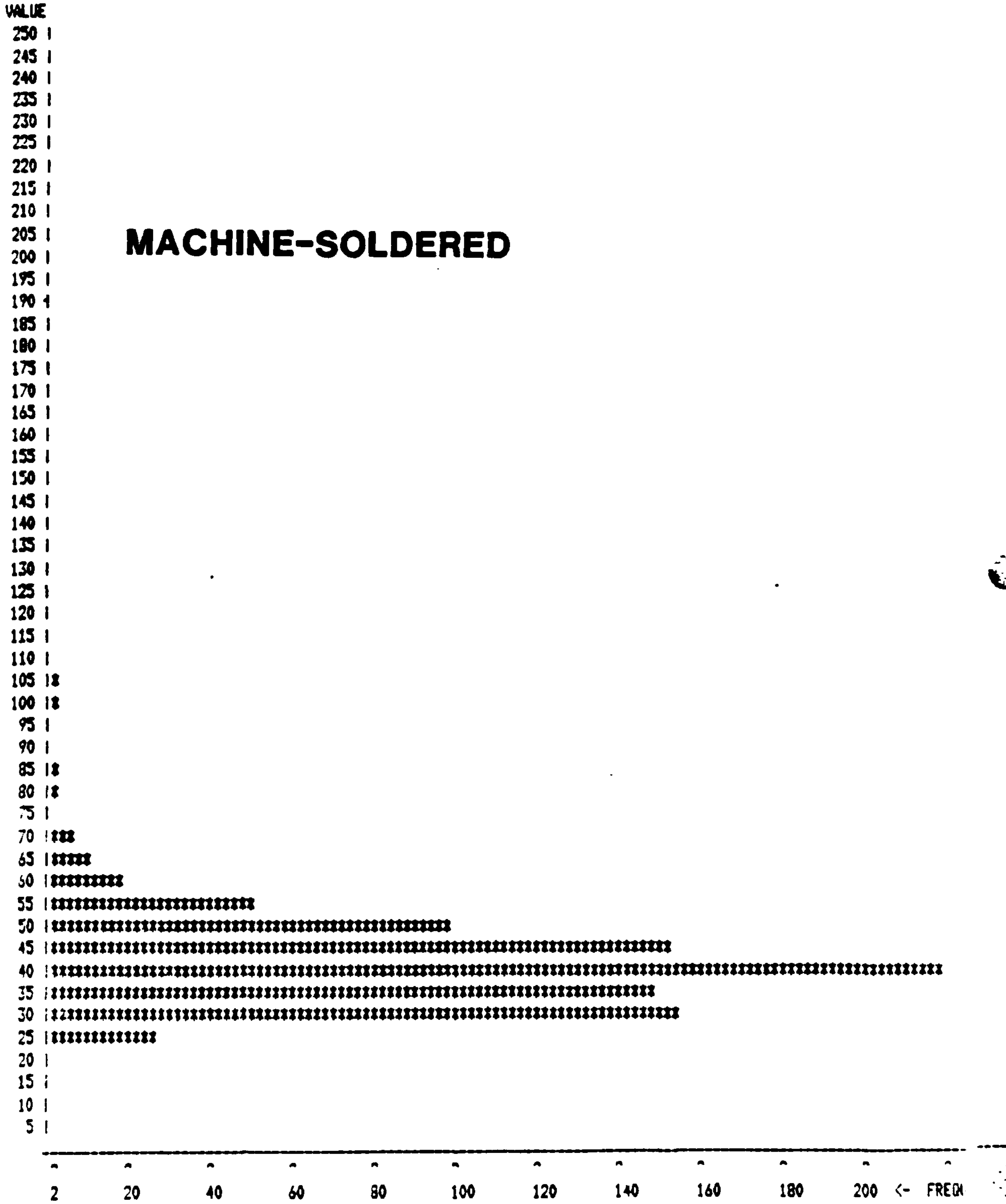
Frequency Distribution Based On > 846 < Total Points DATE: 20-AUG-82 File Name



Plot has been set to a scale of (1/ 1) Each * = 1 Solder Joints, Solder Joints on Plot = 836

TABLE 4. HISTOGRAM OF A DIFFERENT BOARD, HAVING 896 SOLDER JOINTS.

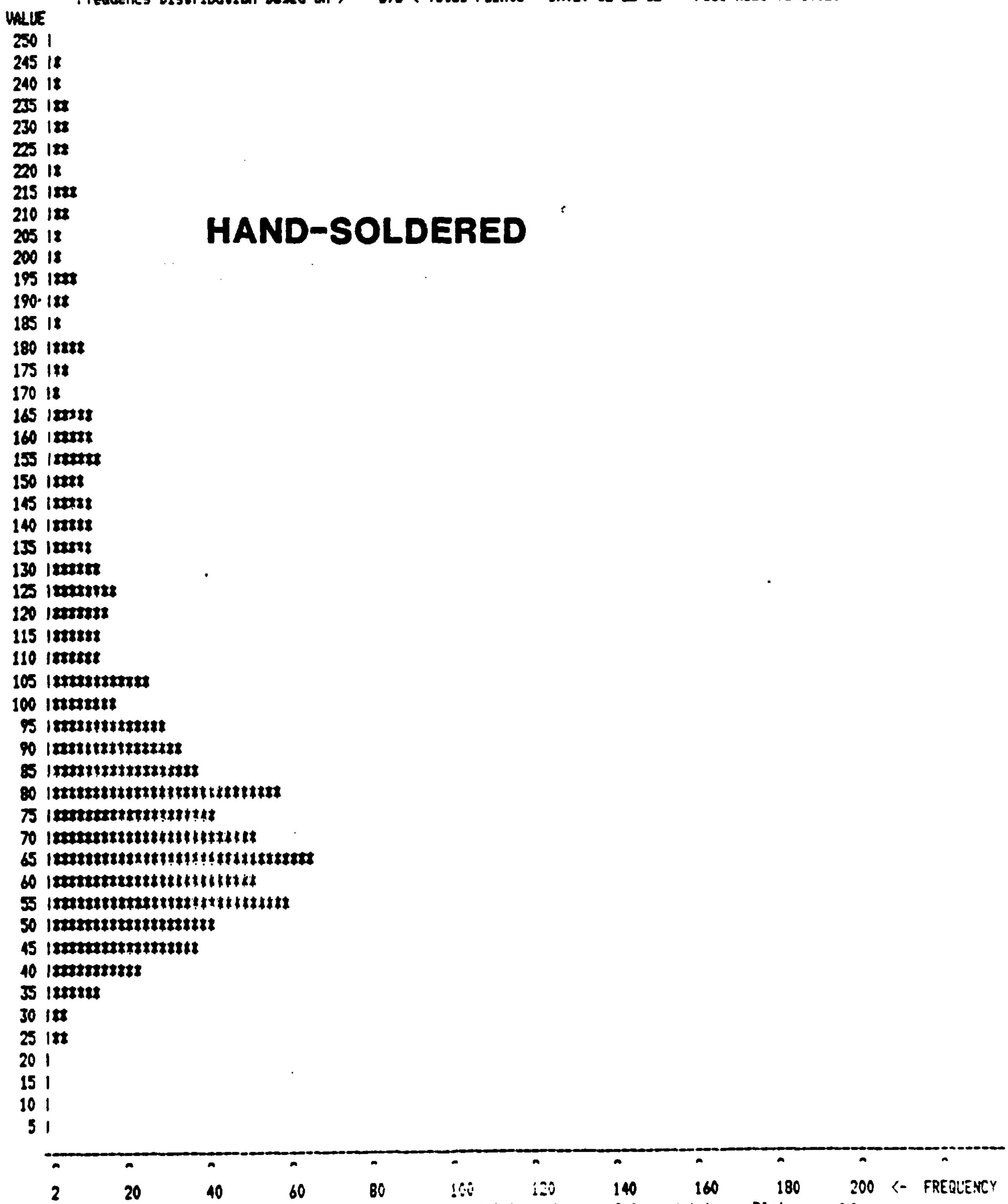
Frequency Distribution Based On > 896 < Total Points DATE: 12-22-82 File Name TEXI.003



Plot has been set to a scale of (1/ 2) Each * = 2 Solder Joints, Solder Joints on Plot = 895

TABLE 5. HISTOGRAM OF A BOARD SIMILAR TO THAT OF TABLE 4 BUT HAND-SOLDERED.

Frequency Distribution Based On > 896 < Total Points DATE: 12-22-82 File Name TEXI.023



Plot has been set to a scale of (1/ 2) Each * = 2 Solder Joints, Solder Joints on Plot = 692

TABLE 6. A MULTI-CUSPED HISTOGRAM INCLUDING SOLDER JOINTS OF THREE TYPES.

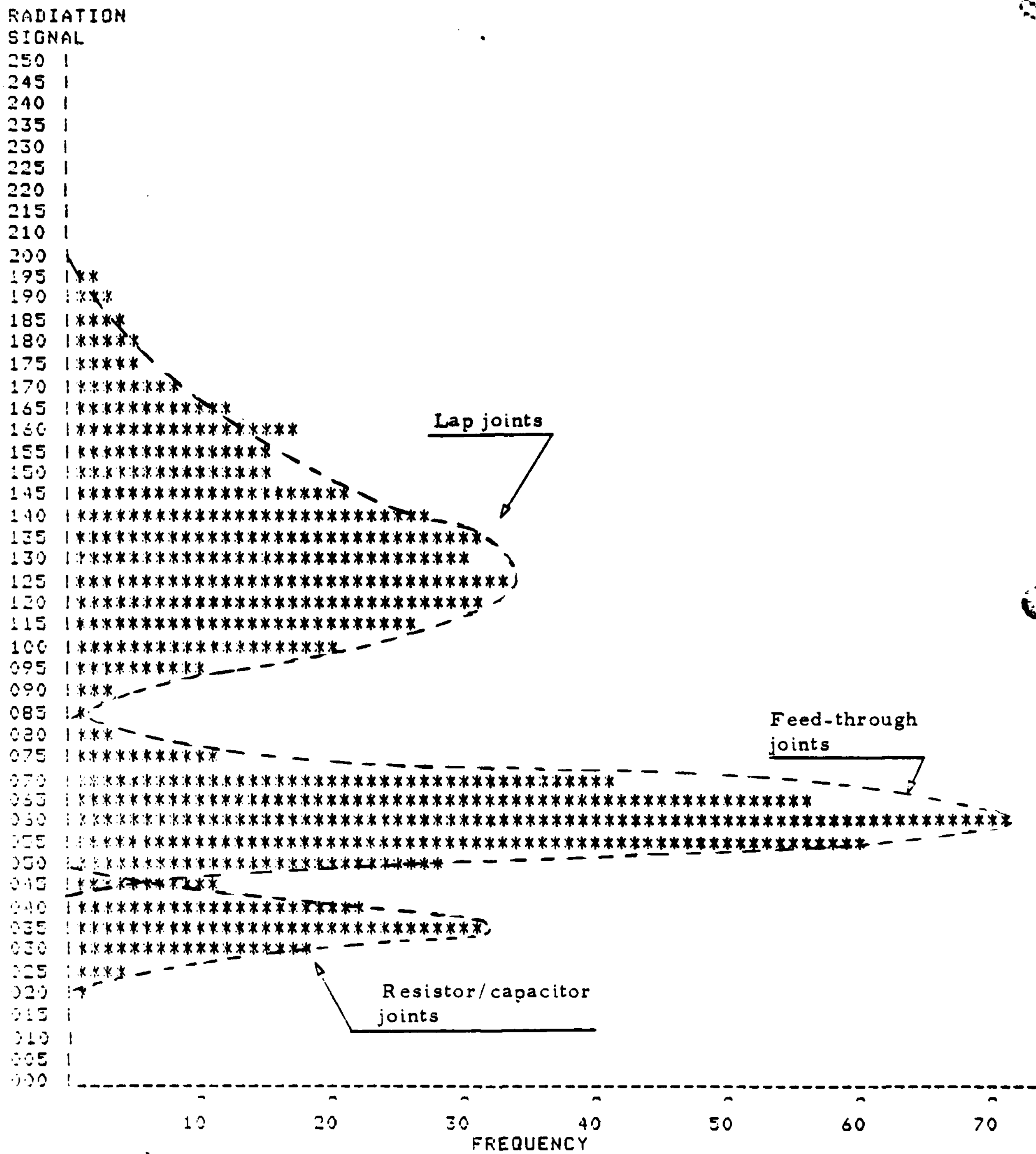


TABLE 7. EXAMPLE OF AN OTHERWISE "GOOD" BOARD CONTAINING A 16-PIN IC HAVING POOR SOLDERABILITY.

```
RADIATION
SIGNAL
250 |**
245 |*
240 |
235 |*
230 |***
225 |****          POORLY
220 |*             SOLDERABLE
215 |              COMPONENT
210 |
200 |*
195 |*
190 |**
185 |
180 |
175 |
170 |
165 |
160 |
155 |
150 |
145 |
140 |
135 |
130 |
125 |**
120 |*
115 |*
100 |***
095 |*****
090 |*******
085 |*********
080 |*********
075 |***********
070 |**************
065 |********************
060 |***************************
055 |*********************************
050 |*******************************************
045 |****************************************************
040 |******************************************************************
035 |**************************************
030 |****************
025 |*********
020 |****
015 |
010 |
005 |
000 |---------------------------------------------------------------------------
              10        20        30        40        50        60        70
                                    FREQUENCY
```

of a single 16-pin IC. The IC had been identified in the original printout as showing higher-than-normal radiation values at all joints.

PROCESS CONTROL

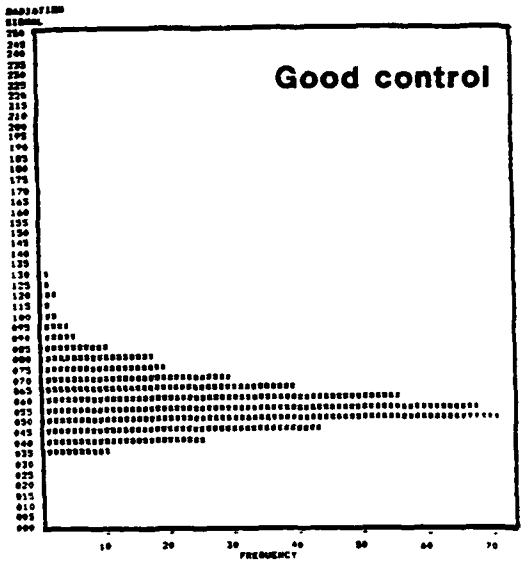
Being thus equipped with the computer's capability to present statistical information, we have available a very powerful tool for monitoring in near-real-time the quality of the soldering process, be it wave soldering or some other.

When the process is optimal, the sequence of histograms corresponding to a group of freshly made, newly tested boards can show at a glance that this is the case. If the process starts to deteriorate, this can be discovered almost at once in terms of the degraded histograms which result. Process deterioration can result from improper values in any of several parameters including machine settings, solder composition, variations in substrate materials, and so forth.

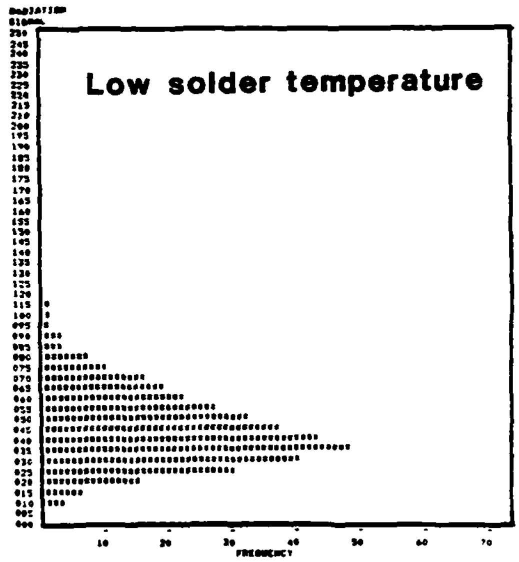
A few illustrations of how the histograms are affected by poor process control are presented in Figure 13. At the upper left is the reference histogram typified by a good board. To the right is illustrated the result of a low solder temperature or too high a conveyer speed. The resulting joints show excess solder and their increased thermal masses show less warming during laser exposure than do normal joints.

The lower histograms in Figure 13 illustrate the effects of metallic contamination of the solder and of various causes leading to cold solder joints.

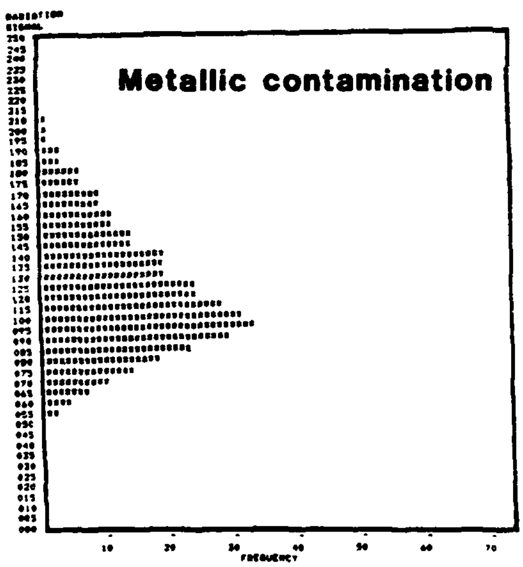
Frequency-distribution-monitoring can be made an automatic feature of Laser/INSPECT through a software change so that the histograms need not be examined visually. The monitoring function can be either simple or sophisticated, according to the user's needs. The simplest capability would consist of counting the number of occurrences of radiation signals above a certain threshold



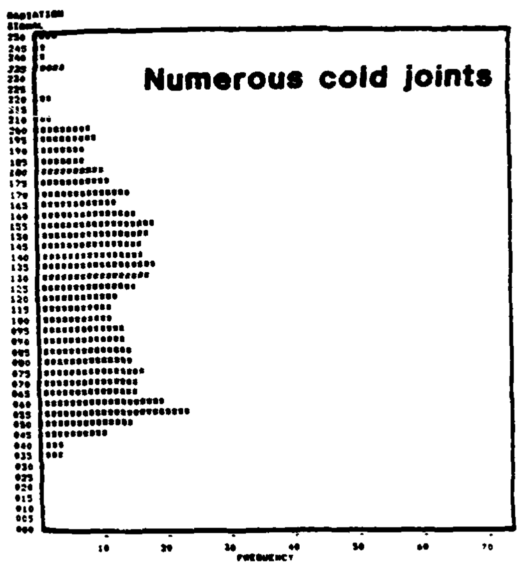
Good process control is shown by narrow frequency distribution.



Low solder temperature or too high a conveyor speed can yield heavy joints.



Metallic contamination in solder causes granular or cloudy solder surfaces.



Cold joints mixed with good joints can result from a variety of causes.

Figure 13. Effect of process variations during soldering.

value. If this number exceeds a predetermined value, an alarm is activated.

The illustrations given thus far have referred only to the quality of the soldering process itself. It is clear, however, that if the post-soldering board-cleaning process is not effective, residual solder flux and/or other materials may remain on the board and these have been shown to cause higher-than-normal readings on Laser/INSPECT. The readings take on one of two forms, depending upon the type and amount of contamination. Small amounts of combustible or evaporable materials are usually "burned off" almost instantly, leading to a high radiation peak and almost instantaneous cooling and leaving the solder joint clean and shiny.

Subsequent laser-beam exposures then yield normal radiation signals. In other cases, the amount of material may be sufficient to cause charring, leaving the solder with a burnt appearance and causing high signals thereafter. Most often, these are high enough to activate the damage prevention circuit, thereby flagging themselves quite readily. In either case attention will be drawn to the fact that surface contamination of the solder joints is present.

Poor process control prior to soldering can also be revealed by the frequency distribution data. In the preceding section we have cited the possible chance occurrence of a poorly solderable IC. It may happen, however, that an entire batch of the same IC's shows the same poor quality, and this would be revealed by the repeated occurrence of the anomalous data on the histograms of the affected boards.

Laser/thermal testing has also been able to reveal an IC which was improperly inserted in a tilted orientation such that there was less lead penetration than normal on one row of pins and more than normal on the other row, leading to abnormalities in the radiation signals. Should this occur consistently as the result of an insertion-process malfunction, it would be another example of a process error which could be discovered by use of the

frequency distribution data.

One can think of many ways in which process deviations will reveal themselves by causing anomalous histograms. Reviewing the few which we have mentioned and adding several more, we can arrive at the following list, which is not necessarily all-inclusive:

Assembly operation:

Improperly inserted components (partial or tilted insertion)
Use of components with poor solderability
Improper board cleaning; presence of debris or contamination

Wave-soldering process:

Improper flux application
Improper preheat
Wrong conveyor speed
Solder temperature out of control
Improper depth of submergence
Solder contamination

Post-cleaning

Imcomplete removal of flux and activator.

COST/EFFECTIVENESS

The use of Laser/INSPECT on a production line can bring about certain intangible benefits in addition to those cost-savings which are amenable to calculation. The intangibles include the enhancement of product reliability and reduction of field failures, improved customer relations, a competitive price advantage, and so forth.

The immediate, tangible cost-savings are those due to a reduced inspection cost and a reduction in warranty repairs.

Inspection Cost

The inspection rates used by production-line inspectors of solder joints are highly variable, depending on the end-use of the product. For commercial

electronics used in consumer products, cursory inspections are used, with typical rates of seven joints per second. At the other extreme, where high-reliability military or space applications are involved, an inspector may be required to spend several seconds in examining each joint.

Even the cursory inspection rate is exceeded by the 10-joints-per-second rate of Laser/INSPECT which, moreover, can work non-stop, around the clock, without rest periods or with its attention diverted. Moreover, its decision threshold does not vary with fatigue or tension, nor does it accidently miss a portion of a board. Its ability to find hidden defects, not detectable by the inspector, is another advantage.

Table 8 indicates how many human inspectors working at 100% efficiency are needed to match the throughput of one Laser/INSPECT system operated at 70% efficiency. Except when competing with superficial examinations by commercial-electronics inspectors, the system can pay for itself in 6.5 months or less. Beyond this point, the labor savings is almost complete because, in automatic operation, the system need be attended by only one operator in order to perform the work of several. Moreover, full-time attendance is not required; the operator can run other systems or carry out the repair of flagged defects while not loading or unloading boards or performing miscellaneous tasks.

<u>Warranty Savings</u>

According to a noted manufacturer of electronics systems, warranty cost is usually expressed in terms of a percentage of sales and is variable according to the environment of the end use. For consumer products used indoors or in benign environments, the cost should not be more than three to four percent of sales. For military, aerospace, outdoor, or severe industrial environments, it may reach 15% to 18%.

TABLE 8.

LASER/INSPECT EQUIVALENTS

ASSUMING: $175,000 cost of L/I system
$ 27,000 annual labor cost for one skilled inspector
L/I inspection speed at 70% efficiency: 7 joints/second (99% REL)

THIS MANY INSPECTORS ARE NEEDED TO INSPECT THE SAME NUMBER OF JOINTS:

NUMBER OF INSPECTORS	JOINTS INSPECTED BY ONE VISUAL INSPECTOR EVERY:			ANNUAL LABOR COST OF ONE 8-HOUR SHIFT	L/I SYSTEM PAYBACK IN MONTHS OF OPERATION		NOTES
	HOUR	MINUTE	SECOND		ONE SHIFT	THREE SHIFTS	
1	24,000	400	7	$ 27,000	78	26	(1)
4	6,000	100	2	$ 108,000	20	6.5	(2)
10	2,400	40	1	$ 270,000	8	2.7	(3)
40	600	10	0.2	$1,080,000	2	0.7	(4)

NOTES: (1) Commercial electronics
(2) Quality Commercial and Industrial Electronics
(3) High Rel non-mil specs
(4) High Rel military and space

TABLE 9. FINANCIAL DATA ON THE TOP SMALL BUSINESS COMPUTER SUPPLIERS.

Totals for the company or for the closest division that includes computers	Sales* ($ millions)	10^6 PCB ft^2 (including multilayer)	10^5 Solder Total (based on 2000 solder joints/ft^2)	10^6 joints faulty (based on a target ratio of 2 faulty joints every 1000 joints.)	10^6 $$ Warranty Cost (based on 3.3% of sales $)
Burroughs	$2,902.4	6.0	12.0	24.0	96
Cado					
Data General	653.9	1.3	2.6	5.2	22
Datapoint	318.8	0.6	1.2	2.4	10
Digital Equipment	2,368.0	5.0	10.0	20.0	78
Hewlett-Packard	1,548.0	3.0	6.0	12.0	51
Honeywell	1,634.1	3.3	6.6	13.2	54
IBM	26,213.0	52.0	104.0	208.0	880
MAI Basic Four	303.8	0.6	1.2	2.4	10
Microdata (McDonnell Douglas)	330.7	0.6	1.2	2.4	11
NCR	3,322.4	6.5	13.0	26.0	113
Texas Instruments	987.0	2.0	4.0	8.0	32
Triad Systems					
Wang	543.3	1.1	2.2	4.4	18
Total USA Comp.	$41,123	82.0	164.0	328.0	1370

Data based on latest annual report ending December 31, 1980

ELECTRONIC BUSINESS/MAY 1981

Table 9 presents some interesting warranty-cost data on some of the leaders in the small-business-computer industry. Altogether, the total warranty cost was $1.37 billion, or three percent of $41 billion in total sales. Of course, this was not all due to faulty solder joints, but assuming that 20% of it was, the savings could have been over $270 million if the defects had been caught in time. And this example is for only one segment of the electronics industry.

ADVANTAGES OF LASER/INSPECT

To conclude our discussion, we present a comparison of human vs. automated inspection in Table 10:

TABLE 10. COMPARISON OF VISUAL AND AUTOMATIC INSPECTION

VISUAL INSPECTION	AUTOMATIC INSPECTION
• Inconsistent, subjective, limited reliability	• Consistent, objective, reliable, in-depth
• Product quality level set by inspectors	• Product quality level set by management
• High inspection and warranty cost	• Low inspection and warranty cost
• Persistent production of defects	• Reduced production of defects

AND OF THE FUTURE:

The Li/6000 has been developed for use with conventional feed-through joints at DIP's and lap joints at flat-pack IC's because the solder joints on today's manufactured PC boards consist almost entirely of these.

There are, however, some new surface-mounted devices being anticipated for future use, comprising leadless chip carriers (LCC's) and chip components.

Visual inspection of their solder joints is especially difficult because the contact areas are hidden by the devices themselves.

Vanzetti Systems has been conducting exploratory tests of such joints, in collaboration with major manufacturers, with promising results. One manufacturer of boards which use chip components has been concerned only with the question of whether solder is present or absent at an intended joint, and the Li/6000 was readily able to demonstrate this distinction. Another manufacturer presented us with an intentionally "good" and "bad" set of LCC solder joints, in terms of quality of surface finish, and the system presented strikingly different histograms distinguishing between the two.

Other work is continuing on the use of the laser/thermal method to probe the integrity of the mechanical bond underneath the device.

In other developmental areas, the possible use of the Li/6000 as a manufacturing tool for reflow-fabrication of solder joints is being investigated. Laser-beam reflow of individual joints, accompanied by continuous thermal monitoring, would offer advantages over present methods. And the possibility of using the system for the reflow-repair of existing joints which had been flagged as defective is also being explored.

ACKNOWLEDGMENT

We are grateful for the support and encouragement of many individuals who have had some connection with our development of Laser/INSPECT. These persons, too numerous to name, are located principally at the USAF Sacramento Air Logistics Center in California, at Battelle-Columbus Laboratories in Ohio, and at Vanzetti Systems, Inc.

Special thanks are given to Jim D. Raby at the Naval Weapons Center for his interest and support.

CUSTOMIZING: THE KEY TO
EFFECTIVE SAFETY REQUIREMENTS
by

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ABSTRACT – This paper addresses the role of the integrating contractor in the implementation of a DoD System Safety Program. Rather than revisiting all the standard system safety requirements and practices, which are well documented, the paper concentrates on the need to customize selected requirements and objectives for an effective and meaningful program. The paper details MDAC-STL's work on the Harpoon missile – citing in particular our effort to translate broad, generic requirements to more specific ones peculiar to the Harpoon.

INTRODUCTION

Program Requirements – "The seller shall conduct a system safety program in accordance with the requirements of MIL-STD-882." This is a frequently used safety requirement statement for DoD programs. It will, certainly, result in the customer's being charged for a safety program, but whether it will ensure an effective program is implemented is doubtful. How effective the program will be is a function of the contractor's desire and ability to "customize" the DoD safety objectives and generalized requirements, translating them into specific criteria for application to his product design and analyses.

Harpoon Weapon System (HWS) – The HWS was designed and developed by the McDonnell Douglas Astronautics Company – St. Louis Division for the U.S. Naval Air Systems Command. This anti-ship missile is designed for launch from aircraft, surface ships, and submarines. Pre-launch and launch are controlled by the Harpoon Command and Launch System, which is interfaced with the launch platform's existing sensors and various fire control equipment. The missile is compatible with several different launchers and features a common body to which aerodynamic surfaces and a booster can be added, as required. The common body consists of a guidance section, warhead section, sustainer section, and control section. The missile inboard profile is shown in Figure 1.

The basic missile inherently constitutes a degree of risk by virtue of certain design features provided to meet mission requirements. It contains high explosives, solid propellants, liquid fuel, pyrotechnics, and RF energy sources.

CUSTOMIZING REQUIREMENTS FOR HARPOON

Hazard Severity Categories – First in the sequence of requirements that need customizing were the hazard severity categories. MIL-STD-882 provides the hazard severity definitions shown in Figure 2.

CATEGORY I	– CATASTROPHIC.	MAY CAUSE DEATH OR SYSTEM LOSS
CATEGORY II	– CRITICAL.	MAY CAUSE SEVERE INJURY, SEVERE OCCUPATIONAL ILLNESS, OR MAJOR SYSTEM DAMAGE
CATEGORY III	– MARGINAL.	MAY CAUSE MINOR INJURY, MINOR OCCUPATIONAL ILLNESS, OR MINOR SYSTEM DAMAGE
CATEGORY IV	– NEGLIGIBLE.	WILL NOT RESULT IN INJURY, OCCUPATIONAL ILLNESS, OR MINOR SYSTEM DAMAGE

FIGURE 2 – MIL-STD-882 HAZARD SEVERITY CATEGORIES

Because these definitions rely on the interpretation of certain key words, such as "system," "major," etc., we had to translate the general definitions into specific terms for the Harpoon application.

The most critical issue was what was to represent the "system" in reference to catastrophic equipment loss. Delivery of the Harpoon missile to an intended target requires proper performance of the launch platform, the Harpoon command

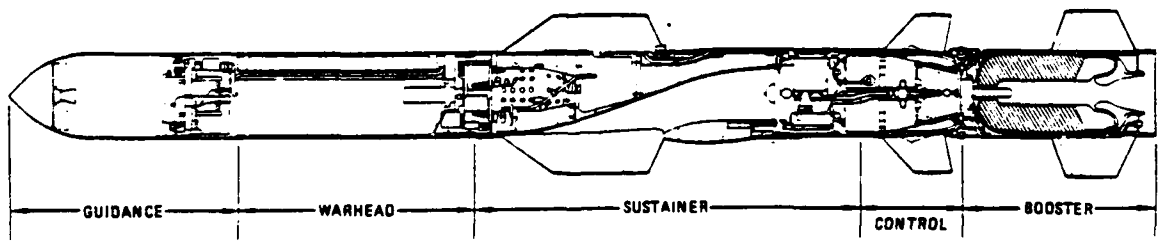

FIGURE 1 – MISSILE INBOARD PROFILE

and launch subsystem (CLS), and the Harpoon missile. All are integral parts of the weapon system. Loss of the CLS or the missile does not preclude the use of other weapons aboard the platform, nor will their loss necessarily jeopardize personnel safety or platform safe return – only the loss of strike capability represented by the HWS. On this basis, it was concluded that to meet the intent of "catastrophic" equipment loss, the system would best be defined to be the launch platform (i.e., aircraft, ship, or submarine), not simply the HWS. This definition related only to equipment loss and did not in any way compromise the identification and categorization of personnel catastrophic hazards.

Further examination led to the need to also better define the hazard severity for missile (equipment) loss. It was evident that a distinction should be made between loss of the missile (or missile function) before launch was intended and missile loss after launch. Losing a missile's functional capability before launch was deemed to represent a significant equipment loss because the HWS effectiveness (number of available missiles) was reduced without intent or planning. Missile loss after launch was considered to be much less significant since the missile expenditure was planned and intentional. To make this distinction, hazard categories were assigned as follows:

- Missile loss (disabled) before launch .... Category III, Marginal
- Missile loss after launch .... Category IV, Negligible

It is significant that "missile loss" was excluded as a candidate for a Category I or II hazard. Such hazards required that special studies be conducted to determine the cause and that reports be given to the customer, who would initiate corrective measures. Consequently, if missile loss were treated as a Category I or II event, all part failures within the missile that could cause flight failure would have been subject to individual safety studies and tracking. This would have resulted in extensive time and money being wasted on an analysis of events that have little or no safety significance. It would also have diluted the effort in identifying and controlling the true safety hazards of the system. Fortunately, the customer and MDAC-STL agreed that missile loss was adequately and more appropriately addressed by the Reliability engineering discipline.

Hazard Identification – Having established the hazard criteria, the next step was to identify the generic hazards of the HWS. These hazards were identified through design reviews and preliminary hazard analyses. The process was performed repeatedly, both for the basic missile and for each unique launch platform application. The primary objective in each case was to identify those hazards that warranted further study. The resulting lists were continuously reviewed with the customer to ensure that both the producer's and the user's insights were reflected in the list development.

Developing the preliminary hazard list is critical to the requirements customizing process. The list provides the baseline for the systematic adaptation of general requirements into specific criteria for the product involved.

Typical hazards identified for the HWS are listed in Figure 3.

SAMPLE FOR ASSESSMENT	• INADVERTENT WARHEAD DETONATION • INADVERTENT BOOSTER IGNITION • INADVERTENT MISSILE RELEASE • INADVERTENT SUSTAINER ENGINE START

FIGURE 3 – HWS TYPICAL HAZARDS

Hazard Assessment – This activity depends most on the contractor's desire and ability. Risk vulnerability to the customer may be limited. Detail in assessment criteria are frequently lacking. Even if criteria exist, compliance rests, for all practical purposes, with the contractor. In short, since customer awareness depends largely on contractor reporting, risk acceptance judgements are frequently made unilaterally by the contractor. Furthermore, if not properly controlled, such judgements can be made by a single safety analyst. For these reasons, MDAC-STL set forth specific assessment criteria for hazard control and established a clear policy of coordinating with USN safety working groups.

How we worked with the hazard of "Inadvertent booster ignition (aboard ship)" illustrates our general approach to hazard assessment. Because this hazard cannot be eliminated (it is inherent in the system), emphasis was given to assessing the adequacy of designed-in protection.

Harpoon Assessment Criteria – Because all mechanical and pyrotechnic safety aspects were adequately controlled by established military specifications, our effort was directed primarily at electrical and electro-mechanical systems analysis. The principal area of concern, therefore, became the potential for inadvertent electrical commands that could activate the mechanical and/or pyrotechnic systems.

The prime objective was to determine the degree of fault tolerance existing in the design for comparison to the current MIL-STD-1658 (CS)[1] firing circuit requirement. This requirement states that "an inadvertent firing shall not be possible without occurrence of at least two independent failures when there is power available to the ignition circuit, and at least three independent failures when no power is applied to the ignition circuit."

The assessment criteria developed were as follows:

1. Analysis Technique – Combinations of events had to be addressed for comparison to the stated requirement. For this purpose, qualitative fault trees were selected as the most effective analysis technique.

[1] MIL-STD-1658 (CS), Shipboard Guided Missile Launching System Safety Requirements, Minimum, 6 September 1974.

2. Failure Modes – Key to the stated requirement was which fault events were to constitute an "independent failure." For example, were crew errors to be considered? Were erroneous commands from interfacing equipment to be counted? Which specific component failure modes were to be included or excluded? All such questions had to be addressed to establish an agreed-upon assessment criteria.

Through close customer coordination, the following criteria were accepted as the basis for system safety assessment (rationale is also given with criteria). It was agreed that identification of all fault events to be considered in a Fault Tree Analysis (FTA) prior to conducting the analysis is impractical.

2.1 Criterion: Fault events (e.g., component failure modes, crew errors, erroneous commands, etc.) will be considered as dictated by FTA development, rather than by pre-analysis decision. In other words, no specific causes of fault events will be excluded from consideration.

Rationale: If the inadvertent loss or presence of a signal by itself or in conjunction with other events can result in a critical condition, it should be identified without regard to potential cause. The cause (or likelihood) of the fault event is best addressed when assessing the significance or need for change – after the fault event has been identified.

2.2 Criterion: Connectors and terminals (and respective failure modes) will be covered as a single entry for "wires" with failure modes of open, short, and induced signal.

Rationale: (a) Analysis and identification of all connectors and terminals can result in considerable additional effort without any significant benefit in identifying critical circuits, and

(b) Limiting terminal analyses to only adjacent pins will not address wire-to-wire shorts in common wire bundles. Analysis of wire-to-wire shorts should be included in safety FTAs. The connectors and terminals are more properly addressed when assessing the potential for inadvertent loss or presence of a critical signal.

These criteria provided a meaningful basis for establishing the degree of risk that could be qualitatively assessed and objectively discussed by technical personnel. We were able to determine that, for the examples in Figure 4, the risk level was acceptably low and that no corrective action was required. For the single-event failures, the NAVAIR System Safety Working Group and the NAVSEA Surface System Safety Subgroup – both composed of customer and contractor personnel – found that fire switch failure could be caused only by a broken switch shaft, and that was an acceptably low risk. They also found the risk of crew error (inadvertently activating the fire switch) to be acceptably low because the push-to-turn and spring-loaded-off features of the switch provided protection against such inadvertent activation. For the dual-event failure possibilities (caused by two shorts in a single connector), it was determined that such failure could be caused by salt water getting into a connector – an acceptably low risk, since all the connectors are located below deck.

EVENTS LEADING TO INADVERTENT BOOSTER IGNITION
(POWER ON)

- SINGLE EVENTS:
  - FIRE SWITCH FAILURE
  - CREW ERROR (FIRE SWITCH CLOSURE)
- DUAL EVENTS (DUAL SHORTS IN A SINGLE CONNECTOR):
  - LAUNCHER SWITCHING UNIT: J06, J07
  - CASUALTY PANEL: J01
  - WEAPON CONTROL – INDICATOR PANEL (WCIP): J04
  - WCIP FRONT PANEL P8

FIGURE 4 – ANALYSIS RESULTS

SUMMARY

An effective safety program requires that the customer's general requirements for risk assessment and control be translated into specific terms that are customized for the program and clearly understood by both contractor and customer. How successful the effort is depends on the contractor's desire and ability, and the degree of visibility afforded the customer. Use of contractor and customer jointly developed assessment criteria has proven effective on the HWS, resulting in a better basis for making and implementing fix/no-fix decisions. The development and promulgation of such criteria will provide a common communication base for contractor and customer risk discussions and dispositions.

THE EFFECT OF MEASUREMENT ACCURACIES AND CALIBRATIONS
ON PRODUCT QUALITY AND PRODUCTIVITY

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THE NEED FOR HIGHER PRODUCT QUALITY AND PRODUCTIVITY IN DEFENSE AND AEROSPACE INDUSTRIES

Pressures to increase product quality and productivity have become a way of life for U.S. industries during the past decade. Although the fiercest competitive assaults have been leveled against consumer products industries and the steel industry, mainly from foreign competitors, the defense and aerospace industries, too, have experienced considerable pressure to increase productivity while maintaining their generally high quality level. The pressures in the consumer products industries have probably leveled off; the pressures in the defense and aerospace industries should be expected to rise further in the years to come.

In the past, inflation has driven up the cost of defense and space procurement while the budgets often did not keep up with inflation. In addition, the mounting strength of our potential military adversaries has created demands of "more bang for the buck." But the turmoil of the consumer products industries has by and large passed by the defense and aerospace industries, and foreign competition here is not significant -- so far. However, it is high time now to get prepared for massive on-slaughts of new competition.

Those consumer products industries which have survived the often lethal assaults from high quality and high productivity of competitors are apt to apply the hard learned lessons of the recent past to defense products and become new, fearsome competitors in defense procurement. And many defense contractors are also exporters of military hardware and must compete with foreign manufacturers in the world market. There, however, it may be argued politcal considerations often come before economic ones, but this argument can cut both ways. In the airframe business, foreign competition is already appreciable and mounting; a similar trend can be observed in the space industry.

But more ominous hardwritings appear on the proverbial wall.

In an article entitled "Tokyo's Buildup - Japan's Arms Industry is Expanding Briskly, with Much U.S. Help," The Wall Street Journal (WSJ - Nov. 26, 1982) describes the rapid growth of Japanese defense industry which, so far, only sells its products to the Japanese government. But that can, and should be expected to, change. Writes WSJ in the quoted article: "Already, the Japanese are making some missiles, radars and other products considered superior to American counterparts."

The IEEE Spectrum (September 1982) notes in an editorial titled "The Space Shuffle" that, although by the 1970's the U.S. was the undisputed leader, now "...all that is changing. France is now an important entity in the space race, as is Japan." The editorial cites a U.S. Office of Technology Assessment (OTA) report released in June 1982 and states: "Japan's... launch rockets are based heavily on U.S. technology....But a pair of consecutive mishaps costing the Japanese an estimated $100 million were traced to probable malfunctions of U.S. equipment...The OTA report concluded: 'Though in the past

the Japanese have relied heavily on the United States, dissatisfaction with U.S. technology can only mean fewer contracts for U.S. firms and more emphasis on indigenous development and/or deals with European companies.' "

Clearly then, the battle for higher quality as well as for higher productivity has just begun in the U.S. defense and aerospace industries.

"THE PRODUCTIVITY--QUALITY CONNECTION"

Perceptive quality control professionals have recognized that product quality and productivity are closely related aspects of what may be called production management. In his examination of the productivity - quality connection, Iervolino (1982) notes in an address under the same title: "Now, in the eighties, given the constraints imposed by regulation, inflation, shifts in jobs skill levels, service and quality demands, and greater international competition, the productivity emphasis is increasingly on effectiveness. Our performance will not only be judged on whether we produce the right things, but whether we produce things right and at the lowest cost...

"....the good news is that the declining rate of productivity growth which has been talked about so intensely over the past several years, is now widely recognized in industry as a problem. The bad news is that like many quality programs, talking about it does not necessarily improve it...Improvements in productivity, like improvements in quality, cannot simply be mandated by management. They must be cultivated through the difficult process of problem solving. The real difficulty in this area is not in understanding that there is a problem, but in solving it.

"Our approach to value analysis and reduction in product cost focuses on the plant and, in fact does result in driving these costs down. Meanwhile the so-called 'hidden plant' costs increase astronomically in the areas of quality costs, such as rework, scrap, warranty, service, engineering change orders, software changes, purchase order changes, supplier rejects and late delivery, inspection errors and quality labor costs. There is today no more effective way to improve productivity than for quality programs to convert these 'hidden plant' costs to productive use."

Iervolino cites Deming (1981) as commenting: "...nobody seems to understand except the Japanese that as you improve quality, you improve productivity."

UNDERSTANDING THE QUALITY - PRODUCTIVITY CONNECTION

Obviously, production costs decrease and productivity increases when a product is made right the first time. It's in deciding whether a product was made "right" that a problem arises which demonstrates another aspect of the many faced quality-productivity connection.

Consider, for instance, a product which must be of a certain size. The product is unacceptable if it exceeds a given high tolerance limit or if it is smaller than a given low tolerance limit. Then take a product which meets the specifi-

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cation and is, therefore, perfectly usable, but whose size is close to the high end of the acceptable tolerance range. If a small error is made in determining the size, the product could be rejected as exceeding the tolerance limit.

Such an error is called an error of the first kind and is often designated as alpha (α). Conversely, if the product in fact just exceeds the upper tolerance limit and the small error in determining its size leads to accepting the product when it actually should have been rejected as not conforming to specifications, an error of the second kind, designated as beta (β), has been committed.

Obviously then, an error of the first kind (α) reduces productivity since it increases the cost of the output of acceptable products regardless of the disposition of the erroneously rejected good product. Both retesting and scrapping cost money. Similarly, an error of the second kind (β) decreases product quality since it causes some bad product to be passed on to the customer while also causing a further loss in productivity through increased warranty or follow-up service costs or decreased customer satisfaction. Both errors coexist in every inspection or measurement process. But while the error of the first kind affects productivity only, the error of the second kind affects both quality and productivity.

ENTER: MEASUREMENT ACCURACY

Acceptance-rejection decisions as described above are made in every manufacturing process, frequently a great many times on components, subassemblies, and assemblies down to the completed product. They are all based on measurements: measurements of length, mass, time, electro-magnetic characteristics, temperature, light intensity, amount of substance, and a large number of combinations and derivations thereof.

Often, more accurate measurements in production, inspection, and testing result in both higher productivity (fewer products erroneously rejected) and higher product quality (fewer non-conforming products being accepted) with the higher productivity which separately accompanies higher product quality. To illustrate the relationship between higher measurement accuracies on one hand and higher product quality and productivity on the other, Tables 1 through 6 have been developed. How the tables have been generated, definitions, and underlying assumptions are explained in the Appendix.

In the tables, measurement accuracy is expressed in terms of the accuracy ratio, i.e. the ratio of product tolerance to total measurement uncertainty. Thus, an 8:1 accuracy ratio involves a measurement twice as accurate (or having one-half of the measurement uncertainty) as a 4:1 accuracy ratio and four times more accurate than a 2:1 accuracy ratio. Figure 1 is an excerpt of Table 1 and describes a typical manufacturing process. It show the fraction of products erroneously rejected (α) and erroneously accepted (β) as a percentage of total products (good and bad) coming down the production line and being measured for acceptance or rejection. Note then that these figures demonstrate the effect of only one acceptance-rejection measurement at the end of the process under consideration.

PRODUCTION PROCESS CAPABILITY: 2 SIGMA
NON-CONFORMING PRODUCT PRODUCED: 4.5 % OF TOTAL

CONSUMER RISK VERSUS PRODUCER RISK FOR OUT-OF-TOLERANCE TEST EQUIPMENT
(IN PERCENT OF TOTAL ITEMS PRODUCED)

WITHOUT GUARD BAND

ACCURACY RATIO	10:1		8:1		5:1		4:1		2:1	
INSTRUMENT CONDITION	α	β	α	β	α	β	α	β	α	β
IN TOLERANCE	0.49	0.38	0.63	0.46	1.1	0.68	1.5	0.80	4.0	1.2

FIGURE 1

The Effect of Measurement Accuracy on Product Quality and Productivity

As Figure 1 shows, the fraction of good product rejected (α) drops by a factor of 2.4 as the accuracy ratio is increased from 4:1 to 8:1. The productivity element related to the cost of rejecting good product for that part of the process which is controlled by this station increases by the same factor. At the same time, the fraction of bad product accepted (β) decreases by a factor of 1.7. Since the cost associated with passing on bad product to the customer is also decreased by 1.7, the total productivity is further increased by this factor.

At a 4:1 accuracy ratio, 1.5% of the total product constitutes good product rejected. Since 95.5% of all product made is good in this example, 94% is good product accepted. Bad product accepted is 0.8%, so that a total of 94.8% of the product is accepted and passed on to the customer. Hence, of all the product which the customer obtains, 0.84% is bad product. Doubling the measurement accuracy to an 8:1 accuracy ratio will decrease the ratio of non-conforming product delivered to the customer to 0.52% or by a factor of 1.6.

Thus, by doubling the measurement accuracy in this example, two productivity elements at this station have increased by factors of 2.4 and 1.7 respectively. While the fraction of non-conforming product which the customer obtains has been cut by a factor of 1.6 and the quality of the delivered product increased correspondingly.

The process under consideration may be the manufacture of a component, subassembly, or assembly, or only one step thereof; and the "customer" may be the final recipient or consumer or the next assembly or manufacturing station down the production line.

PROTECTING THE CUSTOMER WITH "GUARD BANDS"

In high-quality, high-reliability products, the manufacturer will at times reduce the risk to the customer of delivering non-conforming products by accepting a higher risk of rejecting good products in accordance with the principles: "When in doubt, reject the product." When acceptance-rejection

decisions are made by measuring the product, the customer protection is increased by establishing a "guard band" (Figure 3A). The guard band typically is formed by subtracting the measurement uncertainty from the product tolerance so that acceptance-rejection limits are less than the product tolerance. In this way, that part of the good product which is beyond the acceptance-rejection limits is intentionally rejected. The effect of this action is shown in the tables with the heading "With Guard Band." As an example, refer to Figure 2.

PRODUCTION PROCESS CAPABILITY: 2 SIGMA
NON-CONFORMING PRODUCT PRODUCED: 4.5 % OF TOTAL

CONSUMER RISK VERSUS PRODUCER RISK FOR OUT-OF-TOLERANCE TEST EQUIPMENT
(IN PERCENT OF TOTAL ITEMS PRODUCED)
WITH GUARD BAND

ACCURACY RATIO	10:1		8:1		5:1		4:1		2:1	
INSTRUMENT CONDITION	α	β	α	β	α	β	α	β	α	β
IN TOLERANCE	2.8	0.01	3.7	0.01	7.1	0.02	10	0.02	33	0.03

FIGURE 2

The Impact of a "Guard Band"
on Product Quality and Productivity

At a 4:1 accuracy ratio, the guard band practically eliminates the acceptance of non-conforming product while at the same time causing the rejection of ten percent good product. Hence, the near certain elimination of bad product comes at a significant reduction of productivity at this station caused by rejecting an additional 8.5% of good product. This loss in productivity is offset from the gain resulting from delivering virtually no bad product. Depending on the cost of rejecting good product or accepting bad product, the guard band may increase or decrease productivity ranging from dramatically to not at all. Given the potential for massive change of the quality-productivity balance by the establishment of a guard band, such a strategy must be carefully evaluated before it is implemented. The guard band is a sharp, two-edged sword that can annihilate bad products or productivity. The way out of the dilemma posed by guard bands consists of making more accurate measurements.

ENTER: THE CALIBRATION PROGRAM

Measuring instruments must be calibrated from time to time to assure their continued accuracy. A good calibration program may assure that about 90% of all measuring instruments are in tolerance while they are being used. (This is obviously not the same as saying that 90% are in tolerance at recalibration.) Most measuring instruments drift out of tolerance at their own rate.

The drift rate of mechanical measuring instruments can often be associated with their rate of use; drift rate or direction of drift of electrical/electronic measuring instruments is predictable only in exceptional cases.

In a well operated calibration system, few instruments will ever be more than 200% outside the tolerance limits for which they have been designed and calibrated; most out-of-tolerance instruments will be between 10% and 100% out-of-tolerance. Out-of-tolerance conditions exceeding 300% of the original tolerances will rarely be encountered; such conditions mostly manifest themselves to the user of the instrument either by repeatedly yielding suspect values or, very often, by instruments becoming unstable or inoperative in the case of electrical/electronic instruments. These figures are given here only as examples to demonstrate the impact of calibrations on product quality and productivity; they should not be considered normative.

Figure 3 illustrates the impact of out-of-tolerance conditions of measuring instruments on product quality and productivity for our example of production process and accuracy ratio of 4:1 and 8.1. The rapidly growing deterioration of product quality and productivity as measuring instruments are permitted to drift more and more out-of-tolerance is apparent from Figure 3.

PRODUCTION PROCESS CAPABILITY: 2 SIGMA
NON-CONFORMING PRODUCT PRODUCED: 4.5 % OF TOTAL

CONSUMER RISK VERSUS PRODUCER RISK FOR OUT-OF-TOLERANCE TEST EQUIPMENT
(IN PERCENT OF TOTAL ITEMS PRODUCED)

WITHOUT GUARD BAND

ACCURACY RATIO	8:1		4:1	
INSTRUMENT CONDITION	α	β	α	β
IN TOLERANCE	0.63	0.46	1.5	0.80
10% OUT OF TOLERANCE	0.64	0.47	1.5	0.81
25% OUT OF TOLERANCE	0.72	0.51	1.7	0.87
50% OUT OF TOLERANCE	0.98	0.64	2.4	1.1
100% OUT OF TOLERANCE	1.9	1.0	5.0	1.5
200% OUT OF TOLERANCE	4.6	1.6	14	2.1
300% OUT OF TOLERANCE	8.5	2.0	29	2.3

FIGURE 3

Impact of Out-Of-Tolerance Measuring Instruments on Good Product Rejected (α) and Bad Product Accepted (β)

Let us now consider the difference in product quality and impact on productivity between a good calibration program with adequately accurate measuring instruments and a marginal calibration program with marginal measuring accuracies.

As an example, consider case 1, a station with accuracy ratio 8:1 and a calibration program assuring that, on average, 90% of the measuring instruments

are in tolerance and 10% of the measuring instruments are out-of-tolerance by an average of 100%. Compare that with case 2, a station having an accuracy ratio of 2:1 and a calibration program in which 30% of the instruments are in tolerance, 30% are out-of-tolerance by an average of 50%, and 40% are out-of-tolerance by an average of 100%. For the calculations, refer to Figure 4.

Case 1

	α			8:1	β		
90% in-tolerance	0.9 x 0.63	=	0.57		0.9 x 0.46	=	0.41
10% out-of-tolerance by 100%	0.1 x 1.9	=	0.19		0.1 x 1.0	=	0.1
Combined Total			0.76				0.51

Case 2

				4:1			
30% in-tolerance	0.3 x 1.5	=	0.45		0.3 x 0.8	=	0.24
30% out-of-tolerance by 50%	0.3 x 2.4	=	0.72		0.3 x 1.1	=	0.33
40% out-of-tolerance by 100%	0.4 x 5.0	=	2.0		0.4 x 1.5	=	0.60
			3.17				1.17

FIGURE 4

Comparison of Good Measurement Accuracy and
Good Calibration Program (Case 1) with Moderate
Measurement Accuracy and Marginal Calibration Program (Case 2)

Case 1, with good measurement accuracy and a good supporting calibration program, experiences only 0.8% of good product rejected and 0.5% of bad product accepted. Case 2, with moderate measurement accuracy and a marginal supporting calibration program experiences four times more good product rejected with the accompanying loss in productivity, and more than twice the number of bad product accepted with the resulting proportional drop in product quality and the additional loss in productivity.

It should be borne in mind, however, that increased measurement accuracies and better supporting calibration programs usually come at an increased cost. It is entirely possible that lower measurement accuracies and a more relaxed calibration program, down to an optimum point, increase productivity through lower costs while leaving product quality materially unchanged. The point is that both productivity and product quality are simultaneously affected by measurement accuracies and the supporting calibration program. Tables 1 through 6 may provide a basis for evaluating the impact of measurement accuracies and calibrations on productivity and product quality.

CONCLUSION

Defense and aerospace industries must face increasing pressures for higher productivity and product quality. A frequently overlooked area to increase product quality and productivity may be found in higher measurement accuracies, improved calibration support program, or both. The provided tables are intended to give the quality manager a basis for assessing the approximate impact on product quality and productivity from changed measurement accuracies and changed calibration support. As a byproduct, the tables give an example of the close connection between productivity and product quality and of the double "whammy" which productivity suffers from inaccurate measurements, poor calibration support, or both.

ACKNOWLEDGEMENTS

This author is indebted to Mr. George Rice, Manager, Metetrology and Test Equipment, Rockwell International, for the ideas of developing Tables 1 to 6 and investigating the relationships of good product rejected versus bad product accepted for his workshop at the 1982 Symposium of the National Conference of Standards Laboratories. The inspiration furnished by Mr. Iervolino, Director of Quality Assurance and Productivity, Lockheed Electronics Company, through his referenced address at the same Symposium led to linking quality and productivity to measurement accuracies and calibrations.

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Schumacher, Rolf B. F. (1982), "The Effect of Out-of-Tolerance Measuring Instruments on Assemblies," paper presented at the 1982 Workshop and Symposium of the National Conference of Standards Laboratories, Gaithersburg, MD.

TABLES, ASSUMPTIONS, AND DEFINITIONS

Tables 1 through 6 are the results of theoretical analyses to determine producer's risk (conforming or "good" product rejected) and consumer's risk (non-conforming or "bad" product accepted) as a function of measurement accuracies relative to product tolerances (accuracy ratio) and of bias or out-of-tolerance conditions. See also Schumacher (1982).

For the purpose of this analysis, the following assumptions were made:

1. Product Distribution - Products are distributed normally.

2. Process Capability - Calculations were performed on the basis of process capabilities of 2.5-sigma, 2-sigma, and 1.5-sigma, meaning that conforming product is within plus and minus these sigma limits and non-conforming product is outside 2.5, 2, or 1.5 sigma limits respectively (see Figure 1A).

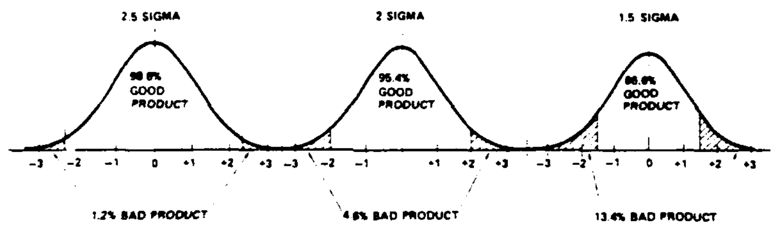

FIGURE 1A

Process Capabilities

3. Accuracy Ratio - The ratio of product tolerance (before adjustment) to the tolerance or accuracy of the instrument measuring the product. Calculations were performed with accuracy ratios of 10, 8, 5, 4, and 2:1.

4. Instrument Tolerance - The accuracy of the measuring instrument. At a 10:1 accuracy ratio and a product tolerance (before any adjustment for guard bands) of 100 units, the measuring instrument is accurate to within 10 units. Instrument tolerances were assumed to be normally distributed for the purpose of the calculations. This may be taken in either one of several ways. It may either be assumed that a number of instruments are used to measure the product tolerance and that their accuracies vary within their tolerance, in this example from -10 units to +10 units; or it may be assumed that a single instrument is used which yields readings which vary within the tolerance limits (from -10 units to +10 units in the example) at repeated measurements of the same quantity; or it may be assumed that a few instruments are used which are periodically recalibrated at which time they may be re-adjusted to their tolerances.

   The instrument tolerance limits were assumed to be at the two-sigma limits of the distribution of the instrument tolerances, so that approximately

five percent of the instruments or their readings are outside the stated conditions. These five percent thus also allow for operator errors.

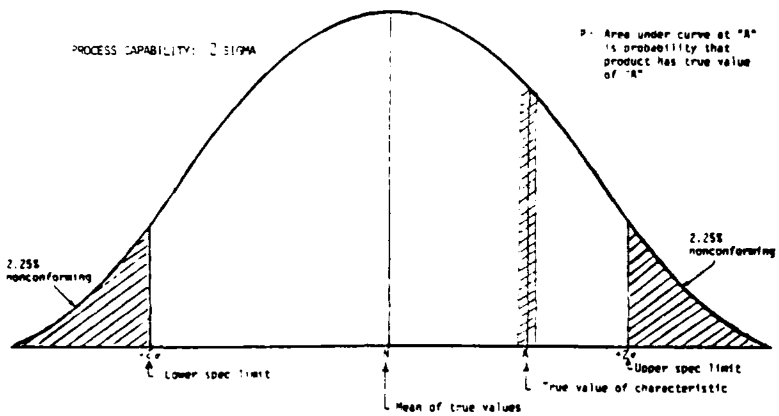

FIGURE 2A

Probability of Occurrence
Conforming and Non-Conforming Product

5. Guard Band - Where guard bands were assumed, the tolerance of the measuring instrument was substracted from the product tolerance to result in acceptance-rejection limits smaller than the product tolerance to allow for the inaccuracy of the measuring instrument. In the example, a guard band of 10 units reduces the acceptance-rejection limits of the product to 90 units; all product beyond these limits is rejected, although some of the product, namely that which has tolerances from 90 to 100 units, is technically good product but is rejected as a precaution (see Figure 3A).

Tables 1 to 6 list, for the various cases of process capability, accuracy ratio, and out-of-tolerance condition, the fractions of good product rejected and bad product accepted as percentages of total products made. Thus, without a guard band, for instance, at a process capability of 2-sigma and a 10:1 accuracy ratio, when the instruments are in tolerance, 0.49 percent of the product is rejected in error (good product) and 0.38 percent of the product is accepted in error (bad product). Since 4.5 percent of the total product is non-conforming, "bad" product, 100 x 0.38/4.5 = 8.4% of the bad product manufactured is accepted in error, on the average. Conversely, 100 x 0.49/ (100-4.5) = 0.51% of all "good" product made is rejected in error in the long run.

But when the instrument tolerance is subtracted from the product tolerance to form a guard band, the chance of accepting a bad product drops dramatically, while the probability of rejecting a good product rises appreciably. This rise then constitutes the price a manufacturer pays for minimizing the risk that bad product is passed on to the customer.

A process capability of 2-sigma, where about 5 percent of the product made is non-conforming and 95 percent is conforming may be regarded as a rather

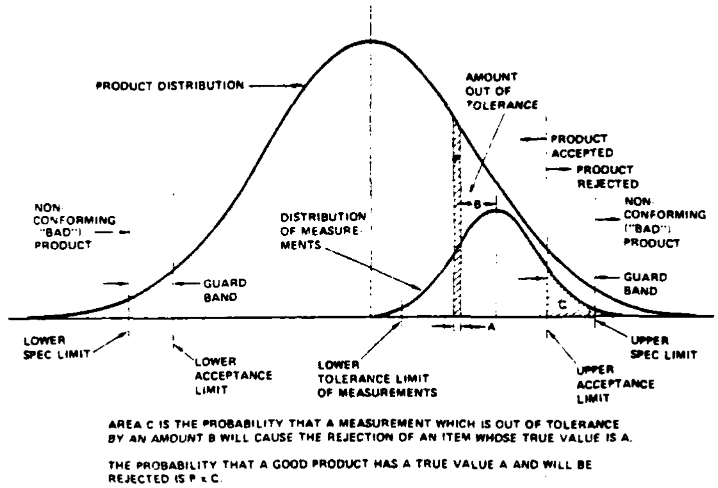

FIGURE 3A

Distributions of Product and Measurements

normal production process, whereas a 2.5-sigma process yielding not more than about 2.5 percent non-conforming product describes a process under considerably better than average control. Processes for the manufacture of near state-of-the-art devices often yield 15 or more percent non-conforming product as exemplified by a 1.5-sigma process. These three cases allow some interpolation and limited extrapolation with sufficient accuracy for most practical purposes.

The tables describe the probabilities of rejecting good product or accepting bad product only for processes under control, i.e., processes for the economic production of a number of like assemblies. Hence, by this definition, more conforming items are produced than non-conforming items, thus resulting in higher probabilities of rejecting good product than accepting bad product. The required process controls necessitate numerous prior measurements on components and subassemblies before the measurements are made which are the subject of these tables. The condition then for these prior measurements is that they be made under the conditions which are normal for the process, e.g., with no more than the usual amount of out-of-tolerance measurements.

The tables show how out-of-tolerance measuring instruments first and foremost increase the cost of production while only to a much lesser extent affecting product quality as long as the production process remains under control.

The guard band itself constitutes an early warning system against excessive consumer risks; it will cause the rejection of a large proportion of product before a significant amount of non-conforming product is accepted. Most likely, the production process will come under suspicion and will be investigated when, for instance, the rejection rate doubles. When a guard

band is established as specified here, in a 2-sigma process, this high rejection rate will be reached before one percent of the product is erroneously accepted. Hence, the extension of the tables to very high rejection rates only serves to illustrate what can be expected to happen. In practice, the whistle will most likely be blown on the process long before such excessive rates of rejection are achieved.

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PRODUCTION PROCESS CAPABILITY 1.5 SIGMA
NON-CONFORMING PRODUCT PRODUCED 13.4 % OF TOTAL

CONSUMER RISK VERSUS PRODUCER RISK FOR OUT-OF-TOLERANCE TEST EQUIPMENT
(IN PERCENT OF TOTAL ITEMS PRODUCED)

WITHOUT GUARD BAND

ACCURACY RATIO	10:1		8:1		5:1		4:1		2:1	
INSTRUMENT CONDITION	α	β	α	β	α	β	α	β	α	β
IN TOLERANCE	0.83	0.72	1.1	0.88	1.8	1.3	2.3	1.6	5.4	2.7
10% OUT OF TOLERANCE	0.85	0.77	1.1	0.9	1.8	1.4	2.4	1.6	5.5	2.8
25% OUT OF TOLERANCE	0.94	0.80	1.2	1.0	2.0	1.5	2.6	1.8	6.3	3.0
50% OUT OF TOLERANCE	1.3	1.0	1.6	1.3	2.7	1.9	3.6	2.2	8.8	3.5
100% OUT OF TOLERANCE	2.2	1.7	2.5	2.1	5.1	3.0	6.8	3.5	18	5.0
200% OUT OF TOLERANCE	4.9	3.0	6.5	3.5	12	4.6	16	5.3	43	6.5
300% OUT OF TOLERANCE	8.1	4.1	12	4.7	21	5.8	29	6.2	69	6.6

TABLE 1

1.5-Sigma Distribution Without Guard Band

PRODUCTION PROCESS CAPABILITY 1.5 SIGMA
NON-CONFORMING PRODUCT PRODUCED 13.4 % OF TOTAL

CONSUMER RISK VERSUS PRODUCER RISK FOR OUT-OF-TOLERANCE TEST EQUIPMENT
(IN PERCENT OF TOTAL ITEMS PRODUCED)

WITH GUARD BAND

ACCURACY RATIO	10:1		8:1		5:1		4:1		2:1	
INSTRUMENT CONDITION	α	β	α	β	α	β	α	β	α	β
IN TOLERANCE	4.5	0.02	5.6	0.02	10	0.03	14	0.04	55	0.07
10% OUT OF TOLERANCE	4.5	0.02	5.8	0.02	10	0.03	14	0.04	55	0.07
25% OUT OF TOLERANCE	4.5	0.03	5.9	0.03	10	0.05	14	0.07	56	0.12
50% OUT OF TOLERANCE	4.7	0.08	6.1	0.09	11	0.14	15	0.18	58	0.31
100% OUT OF TOLERANCE	5.3	0.36	7.0	0.44	13	0.67	18	0.81	[illegible]	1.4
200% OUT OF TOLERANCE	8.1	1.7	11	2.0	21	2.9	29	3.4	69	5.0
300% OUT OF TOLERANCE	12	3.0	16	3.6	32	4.8	43	5.3	84	5.5

TABLE 2

1.5-Sigma Distribution With Guard Band

PRODUCTION PROCESS CAPABILITY 2 SIGMA
NON-CONFORMING PRODUCT PRODUCED 4.5 % OF TOTAL

CONSUMER RISK VERSUS PRODUCER RISK FOR OUT-OF-TOLERANCE TEST EQUIPMENT
(IN PERCENT OF TOTAL ITEMS PRODUCED)

WITHOUT GUARD BAND

ACCURACY RATIO	10:1		8:1		5:1		4:1		2:1	
INSTRUMENT CONDITION	α	β	α	β	α	β	α	β	α	β
IN TOLERANCE	0.49	0.38	0.63	0.46	1.1	0.68	1.5	0.80	4.0	1.2
10% OUT OF TOLERANCE	0.50	0.39	0.64	0.47	1.1	0.69	1.5	0.81	4.2	1.3
25% OUT OF TOLERANCE	0.56	0.42	0.72	0.51	1.3	0.74	1.7	0.87	4.8	1.3
50% OUT OF TOLERANCE	0.75	0.53	0.98	0.64	1.8	0.91	2.4	1.1	7.2	1.5
100% OUT OF TOLERANCE	1.4	0.85	1.9	1.0	3.6	1.4	5.0	1.5	16.3	2.0
200% OUT OF TOLERANCE	3.3	1.4	4.6	1.6	9.7	2.0	14	2.1	[illegible]	2.3
300% OUT OF TOLERANCE	5.9	1.6	8.5	2.0	19	2.2	29	2.3	79	2.2

TABLE 3

2-Sigma Distribution Without Guard Band

PRODUCTION PROCESS CAPABILITY 2 SIGMA
NON-CONFORMING PRODUCT PRODUCED 4.5 % OF TOTAL

CONSUMER RISK VERSUS PRODUCER RISK FOR OUT-OF-TOLERANCE TEST EQUIPMENT
(IN PERCENT OF TOTAL ITEMS PRODUCED)

WITH GUARD BAND

ACCURACY RATIO	10:1		8:1		5:1		4:1		2:1	
INSTRUMENT CONDITION	α	β	α	β	α	β	α	β	α	β
IN TOLERANCE	2.8	0.01	3.7	0.01	7.1	0.02	10	0.02	33	0.03
10% OUT OF TOLERANCE	2.8	0.01	3.7	0.01	7.2	0.02	10	0.02	33	0.04
25% OUT OF TOLERANCE	2.8	0.02	3.8	0.02	7.3	0.03	10	0.03	34	0.06
50% OUT OF TOLERANCE	3.0	0.04	4.0	0.05	7.9	0.07	11	0.09	37	0.15
100% OUT OF TOLERANCE	3.5	0.20	4.9	0.23	10	0.34	15	0.40	50	0.62
200% OUT OF TOLERANCE	5.9	0.85	8.5	1.0	19	1.4	25	1.5	79	2.0
300% OUT OF TOLERANCE	9.3	1.4	14	1.5	32	2.0	48	2.1	93	1.7

TABLE 4

2-Sigma Distribution With Guard Band

PRODUCTION PROCESS CAPABILITY 2.5 SIGMA
NON-CONFORMING PRODUCT PRODUCED 1.2 % OF TOTAL

CONSUMER RISK VERSUS PRODUCER RISK FOR OUT-OF-TOLERANCE TEST EQUIPMENT
(IN PERCENT OF TOTAL ITEMS PRODUCED)

WITHOUT GUARD BAND

ACCURACY RATIO	10:1		8:1		5:1		4:1		2:1	
INSTRUMENT CONDITION	α	β	α	β	α	β	α	β	α	β
IN TOLERANCE	0.21	0.14	0.28	0.17	0.53	0.25	0.74	0.30	2.6	0.43
10% OUT OF TOLERANCE	0.22	0.15	0.29	0.16	0.55	0.25	0.76	0.30	2.7	0.44
25% OUT OF TOLERANCE	0.25	[illegible]	0.33	0.19	0.62	0.27	0.87	0.32	3.2	0.45
50% OUT OF TOLERANCE	0.34	[illegible]	0.45	0.24	0.91	0.37	1.3	0.38	[illegible]	0.50
100% OUT OF TOLERANCE	0.66	0.31	0.92	0.37	2.2	0.49	[illegible]	0.53	14	0.59
200% OUT OF TOLERANCE	[illegible]	0.52	[illegible]	0.59	[illegible]	0.62	11	0.62	45	0.62
300% OUT OF TOLERANCE	[illegible]	0.61	[illegible]	0.61	16	0.62	[illegible]	0.62	85	0.61

PRODUCTION PROCESS CAPABILITY 2.5 SIGMA
NON-CONFORMING PRODUCT PRODUCED 1.2 % OF TOTAL

CONSUMER RISK VERSUS PRODUCER RISK FOR OUT-OF-TOLERANCE TEST EQUIPMENT
(IN PERCENT OF TOTAL ITEMS PRODUCED)

WITH GUARD BAND

ACCURACY RATIO	10:1		8:1		5:1		4:1		2:1	
INSTRUMENT CONDITION	α	β	α	β	α	β	α	β	α	β
IN TOLERANCE	1.3	0.00	1.6	0.00	4.0	0.01	6.1	0.01	28	0.01
10% OUT OF TOLERANCE	1.3	0.00	1.8	0.00	4.0	0.01	6.2	0.01	28	0.01
25% OUT OF TOLERANCE	1.3	0.01	1.9	0.01	4.2	0.01	6.4	0.01	29	[illegible]
50% OUT OF TOLERANCE	1.4	0.02	2.0	0.02	4.7	0.03	7.4	0.03	34	0.05
100% OUT OF TOLERANCE	1.8	0.07	2.7	0.09	6.9	0.22	11	0.15	51	[illegible]
200% OUT OF TOLERANCE	3.5	0.30	5.5	[illegible]	15	0.49	27	0.33	85	0.54
300% OUT OF TOLERANCE	[illegible]	0.52	10	0.59	[illegible]	0.65	[illegible]	0.62	97	[illegible]

α GOOD PRODUCT REJECTED - PRODUCER'S RISK
β BAD PRODUCT ACCEPTED - CONSUMER'S RISK

TABLE 5

2.5-Sigma Distribution Without Guard Band

TABLE 6

2.5-Sigma Distribution With Guard Banc

CALIBRATION:

THE ESSENTIAL INGREDIENT OF EFFECTIVE TOTAL QUALITY ASSURANCE

by

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METRON CORPORATION

ABSTRACT

It has been incontestably demonstrated over the years that periodic calibration of all measuring devices associated with the development, manufacture, or testing of a product is fundamental to the rigid control of product quality. Recently, it has been shown that a properly constituted and supported calibration program is also a potent and vital tool in the implementation of a vigorously effective cost avoidance program.

The evidence supporting these two theses is overwhelming, particularly in the higher technology industries. Quality and cost conscious management will, therefore, promote a calibration program which aggressively supports the entire life-cycle of a product.

But how should such an effective calibration program be developed, implemented and controlled? A properly designed calibration program, directed by a professional metrologist and supported by a dedicated and well-trained staff of para-professionals, can be implemented as a fully recognized independent arm of the overall quality organization. As such, it can be a vital element in the assurance that products meet planned quality requirements, are delivered on schedule, are within or under budget, and provide reasonable profit margins.

Numerous examples of horrendously large costs associated with calibration programs in the past, especially in the defense industries, are unwarranted. As vital as their function is to cost effectiveness and product quality, they are nevertheless peripheral service functions. On the other hand, the vital need for effective calibration programs must not be lost through shortsighted management or inadequate financing.

The delicate balance between the scope of a calibration program and activity requirements can only be achieved by a competent and adequately equipped staff lead by a technically competent director who is sensitive to present and future activity requirements and able to relate calibration program responses to management goals.

Presented at the 7th Annual Soldering Technology & Product Assurance Seminar, 23 February 1983, China Lake, California

INTRODUCTION

The certainty of a measurement can be no better than the accuracy of the instrument performing the measurement. The accuracy of a measuring instrument is dependant upon its design, state of repair, and the validity of its most recent recalibration. The necessity of periodic recalibrations of measuring instruments is fundamental to even a minimal control and assurance of product quality and has been expounded voluminously in the literature.

Juran[1], Deming[2], Hayes and Romig[3], among others, have all written on the importance of calibration during the manufacturing phases. Hayes[4,5], on the other hand, in a classic paper written in 1962, demonstrated that rigid recalibration control is as important during the more conceptual phase of a product as it is during development and production.

Both government and private industry has recognized the need for periodic retest (recalibrations) of measuring devices. All fifty states as well as hundreds of local jurisdictions, have enacted clearly defined measurement standards (or weights and measures). The military vigorously enforces such recalibration standards as MIL-STD 45662, MIL-Q-9858, and MIL-Q-21549, and publishes such guidelines as MIL-HDBK-52. Civilian agencies such as NASA, FAA, DOT, FCC, and FDA all enforce documents mandating calibration control of test instrumentation. The Congress of the United States sponsored and published a very penetrating and disturbing study[6] on the subject. Thus, one might say that proper periodic recalibration of measuring devices is not only necessary, desirable, and fundamental to the control of product quality, but is also the law of the land!

CALIBRATION AS A PROFIT CENTER

While much has been written concerning the technical justifications for periodic calibrations, few have dwelled upon the economic advantages to be gained by the implementation of a program for the effective control of measuring tool accuracy. Indeed, much has been said about the costs generated by metrology (calibration) programs, but little about their cost avoidance functions. Reluctances to wholeheartedly embrace these cost avoidance procedures can be traced to the imperative nature of the management fiats summarized above, as well as most peoples' reluctance to being required to do anything, no matter how beneficial (or profitable) the requirement may be. Couple this natural human tendancy with the economic thinking presently being expounded by many "schools of business" and we have our existant economic cesspool-a fertile breeding ground for the treasonous

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attitudes towards costs, quality, profits, and the customer which is surely causing this nation to lose its technological and production eminance to other nations. (These truisms were more throughly explored in an earlier paper[7].)

Recently, Schumacher[8] and others [9,10] have been quantitatively exploring the premise that, when properly constructed, a calibration program cannot only be cost effective, but, a source of considerable cost savings. Even more important it can become a vital focus for cost avoidances. Admittedly authors such as these, irrespective of their credentials and the irrefutability of their findings, have often been treated as idealistic dreamers or, even worse, as heritical evangalists by a large percentage of the so-called "business managers" referred to above. The validity of the Metrology (or Calibration) Operations Center being truly a cost avoidance (or even a profit) center, is a mathematically precise scientific fact.

CALIBRATION AS AN ELEMENT OF TOTAL METROLOGY

But how do we "get there from here"? How do we change (or institute) a metrology/calibration function such that it will become a source of profit rather than a burden? How do we prepare ourselves for this economic millinium when it occurs for each of our own organizations (at least as far as the metrology/calibration activity is concerned)?

It must first be recognized that no such activity, to be viable, effective, and efficient has been or ever can be created in a vacuum. All such activities must be designed, equipped, staffed, and directed to totally service (i.e., both supplement and compliment) the needs of the product and the facility conceiving, developing, and/or producing that product. Or to express it another way, the total metrology efforts, including the instrument calibrations, must be "<u>product oriented</u>". This was a catchy buzzwork term twenty years ago, but it is non-the-less true today. The total capability for the commission of a proper periodic recalibration effort must be completely designed with the total product needs as the sole consideration. The program must include intense concentration on the staffing as well as adequate attention to the equipment and the environmental facility requirements.

A metrology/calibration activity is, or should be, a balanced combination of people, equipment and an environment facility. This fact should not be so startling, for all activities are combinations of people, equipment and the facilities to house them. This is true no matter if we are speaking of banking, homemaking, aircraft building, or zoo keeping. However, different activities place different emphasises on each of the elements.

A properly constituted metrology/calibration organization is one that is people intensive. The quality and organization of the staff is all-important. Indeed, the great, late electro-metrologist G. D. Vincent[11] once said, "I will make any measurement you wish, in a tent at the North Pole, using old bailing wire and second-hand chewing gum, IF YOU CAN AFFORD IT". What Vincent was trying to show is that, in measurement related activities, the factor of competant personnel is all important, and that properly qualified personnel can overcome many handicaps of equipment or environment at the expense of time (and of course time costs money). The corollary of this is that the finest facility with the best equipment attainable cannot function cost-effectively without a commensurate staff.

But, unfortunately, this was not the pattern during the late fifties, sixties and early seventies. Aerospace/defense money was abundant to "close the measurement gap" exposed by the launching of Sputnik. Some smooth talking, suede shoed, martini buying equipment suppliers allied with gullible but glib metrology charlatans convinced unknowing management to invest hundreds of millions of dollars in horrendous overkills usually not at all product oriented. These "metrological Taj Mahals" appeared to be dedicated more to self gratification than to the quality of the product and to cost effectiveness. These masoleums were often staffed by bargaining unit drones, lead by non-professionals and managed by non-technical, politically oriented individuals. Little wonder that many of the metrology/calibration functions today are so often held in contempt and suffered to continued existence only upon a "necessary-evil-of-customer-requirements" basis.

DEFINITIONS

At this point it might be well to pause and to define certain terms which will be used in this discussion. We have up until now been using the terms "calibration" and "metrology" almost interchangeably, implying that they are one in the same. Such is not the truth as was pointed out by Tobey[12], nor were we intending to mislead the reader.

The term "metrology" has usually been defined too simplistically as "the science of measurement". A more complete definition is offered by Simpson[13]:

> "Metrology is defined as the science of measurement and if broadly construed would encompass the bulk of experimental physics. The term is usually used in a more restricted sense to mean that portion of measurement science used to provide, maintain, and disseminate a consistant set of units or to provide support for the enforement of equity in trade by weight and measurement laws, or to provide data for quality control in manufacturing."

"A measurement is a series of manipulations of physical objects or systems according to a defined protocol which results in a number. The number is proported to represent the magnitude (or intensity) of some quantity (...) embodied in the test object. This number is acquired to form the basis of a decision effecting some human goal or satisfying some human need, the satisfaction of which depend on the properties of the test object. These needs or goals can be usefully viewed as requiring three general classes of measurements."

1. Technical: This class includes those measurements made to assure dimensional compatibility, conformation to design specifications necessary for proper functions or, in general all measurements made to insure fitness for intended use of some object.

2. Legal: This class includes those measurements made to insure compliance with a law or regulation. This class is the concern of weights and measures bodies regulators, and those who must comply with those regulations. The measurements are identical in kind with those of technical metrology, but are usually embedded with a more formal structure. Legal metrology is much more prevalent in Europe than in the United States, although this is changing.

3. Scientific: This class includes those measurements made to validate theories of the nature of the universe to suggest new theories. These measurements which can be called scientific metrology, properly the domain of experimental physics, present special problems........"

How does metrology relate to calibration, the term used in the title of this paper? And how does it relate to the problems of organization for optimum calibration, the theme of this discussion? To satisfy this need, let us adopt these definitions:

Metrology (As an organization): That overall function concerning any aspect of the measurements of physical quantities involving the entire width of the spectrum of measurement disciplines as well as in a full depth from esoteric measurement standards downward through the more work-a-day calibration and maintenance of testing and measuring equipment, as well as further on downward through the most mundane handling and accountability functions. Also included in this chain is the development and analysis of measurement requirements, devices,

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procedures, etc., as well as the necessary measurement related consulting and advisory services to users.

From this we can see that a calibration activity is an integral (and we should point out, inseparable) component of a metrology function and we can define it as follows:

Calibration (As an Organization): That functional capability activity which tests, calibrates, and provides physical maintenance for all of the test and measuring equipment used by the organization of interest to manufacture and develop products or provide services.

In the metrology definition above we also mentioned component activities other than calibration; to complete this set, let us define them:

Reference Standards Activity: That functional capability activity which maintains the physical artifacts of measurement standards at the organization of interest and disseminates the embodied quantities as required and/or directed.

Metrological Engineering and Analysis Support Activity: That functional capability activity which furnishes all technical support, not directly involving the handling of measurement artifacts, to the balance of the metrology function, and which provides metrological technical consulting support to all other activities in the organization.

Metrology Administrative Service Support Activity: That functional capability activity which furnishes all non-technical support to the balance of the metrology function as well as all non-technical interface between the metrology function and other activities of the organization.

Now that we have defined the organizational terms we will be using, let us define certain hardware terms which are used:

Standard: An artifact which provides a physical embodiment of a measurement quantity available in such a manner as to be useful. For the purpose of this discussion, we will consider as standards only those devices and types of devices which are rarely if ever used for direct comparison to test equipment or products, but which are regularly used to calibrate Calibration Equipment. (Note: These hardware standards are sometimes referred to as

Measurement Standards in order to differentiate from forensic, "paper", or other software type standards; in Europe such documentary standards are often referred to as "normalizations" to avoid this source of confusion.)

Calibration Equipment: Those devices which are regularly used to calibrate test equipment or measurment systems.

Test Equipment: All other devices which are used in measurement and testing during the manufacturing, development and service of a product.

Measurement Capability: The ability to make, or cause to be made, a specified measurement in discipline and type to the required level of uncertainty based upon the requirements of end use or product, and to make that measurement traceable to specified national, absolute, or corporate standards.

Measurement Capacity: The ability to make or cause to be made sufficient measurements within specific Measurement Capability in such a timely and cost-effective manner as to not adversely affect either schedule or costs of the end product or service

ORGANIZATIONAL CONCEPTS

While the title of this discussion is "Calibration: The Essential Ingredient of Effective Total Quality Assurance", above definitions tend to prove that metrology is even more essential and that calibration is but an inseparatable element of an overall total metrology function. Thus we may assume that it is not practical in cusory overview such as this to attempt to examine an effective Calibration Activity by itself. For a proper perspective we must look at the entire Metrology Organization with the Calibration Activity as its key element.

In a facility devoted to the creation of a product, be that product either consumer hardware or research, the Calibration Activity exists only to support the movement of that produce from conception to delivery. The other elements of metrology exist primarily to support Calibration in this endeavor and, secondarily, to support the overall Quality Function. These other elements may be metrologically more profound (such as Reference Standards), or technologically superior (such as Metrological Engineering and Analysis Support), or even administratively more sophisticated (such as Metrological Administrative Service Support). But, all of them are peripherial service functions whose existance can only be justified by their support of the Calibration Activity in its mission.

How does one achieve an efficient functional unit when it may appear that higher technical level personnel are subordinated to an allegedly inferior technical support activity?

The clue to the answer to this question is contained within the question itself: The word personnel. Personnel means people, generally more than one person. And when you have more than one person you must have some sort of organization or you have anarchy - technological or political. It is sometimes felt that groups of dissimiliar people cannot be organized into an intergrated organization, particularly in technical organizations. However, it is both feasible and possible to organize groups of dissimilar people for the purposes of mutual support by making them organizationally co-equal and reporting to the same manager- a professional who must be personally knowledgeable of every function under him and responsible for the inter-dependancies of each of the several component activities within the Metrology Organization.

Let us propose a metrology organizational structure by defining the function and responsibilities of each of our recommended organicational units. And, most importantly, let us draw a technical and psychological profile of the key individuals who should head up each critical unit.

The most important aspect of a metrology organization is that it be headed by an Administrative Metrologist reporting to high levels in the Quality Organization and supervising four subordinate units. It should be noted that while this organization generally reports through the Quality channels, such is not mandatory. It can report anywhere provided it reports high enough in the overall organization (corporate or division). Of equal importance is that there exists both on the part of top management and line management a confidence and willingness to make it work. Such an idealized recommended organizational structure is graphically depected in Figure 1.

It is headed by a manager whose qualifications we will discuss below under "Administrative Metrologist". He has four subordinate units reporting to him. They are:

1. Calibration and Maintenance

2. Reference Standards

3. Metrology Engineering and Analysis Support

4. Metrology Administrative Services and Support

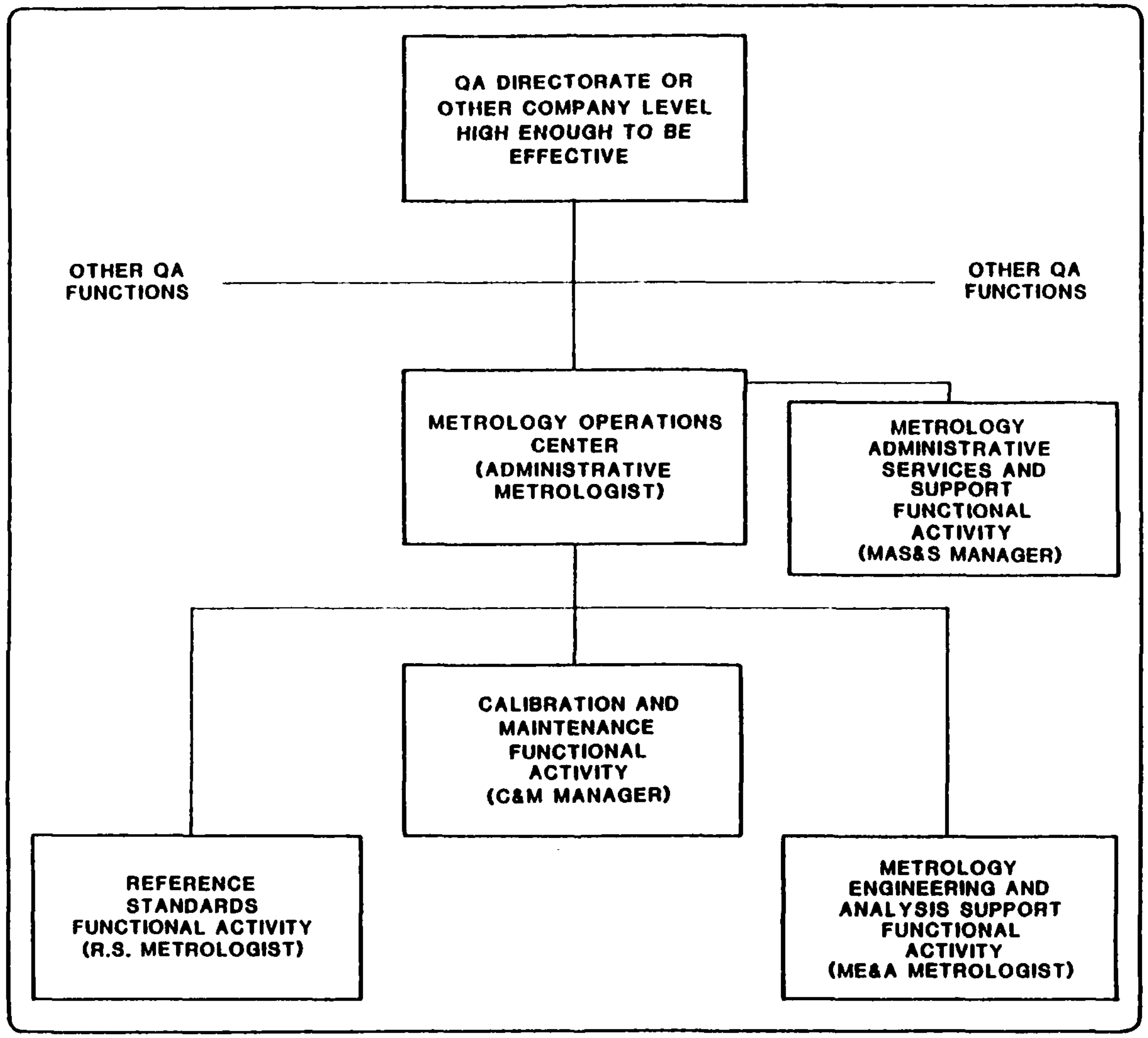

FIGURE 1
RECOMMENDED IDEAL METROLOGY ORGANIZATION

No metrology operation can realize cost avoidance unless it places maximum emphasis upon the actual calibration and maintenance function. All other functions, no matter how necessary, must be considered peripheral and supportive to the calibration and maintenance function i.e., they have no reason to exist except to provide service and support to those performing the calibration and maintenance. However, effective and efficient calibration cannot exist without them.

The organization shown in Figure 1 emphasizes this important concept and insures the high degree of support which is necessary to make the calibration and maintenance functions efficient and cost effective. It also facilitates the creation and continual updating of "A Center of Metrological Competence" capable of effectively supporting the entire facility. And, even more important, having all of the support functions report to the same individual places the responsibility for the timely, economic and quality performance of these support services directly on that manager - the Administrative Metrologist. Or, to paraphrase former President Truman, "The buck stops there".

This unification of calibration activities under a single administration was both economically and technically justified by a study conducted at public expense. Because the study was made only of federal facilities, the results have been generally overlooked in the private sector despite the many lessons which can be learned from the analysis.

The United States General Accounting Office (GAO) conducted this extensive study of Federal Government Metrology operations. A very thorough report[6] on this study was issued in June of 1977. Primary among the many discrepancies the GAO found prevailing in the Federal Government were two which also exist in many non-Federal organizations as well.

1. There is a lack of intra-agency and inter-agency coordination and planning with respect to the calibration (verification) of precision measuring and test equipment.

2. This lack of coordination and planning results in duplication of facilities and hence unnecessary expenditures.

As a result of this and many other disclosures in the GAO report, the Director of the Office of Management and Budget (OMB), on August 27, 1977, issued a directive on the letterhead of the Office of the President of the United States and addressed to the Secretary of Commerce ordering the National Bureau of Standards (NBS) to ". . . assume the lead for coordinating improvements in the management and use. . . of the Federal Precision Measuring and Test Equipment (PMTE)". What

was not totally understood at the time was the enormity of the task. NBS was overwhelmed and hired an outside consultant (Metron Corporation) to analyze this massive problem, to divide it into manageable elements, and to assign priorities. Metron's final report was issued on October 19, 1978[16]. High on their priority list of study tasks defined was (actually third out of ten) was the consolidation of Federal Government Calibration Facilities. This recommendation included by implication the reorganizational changes necessary to implement and optimize the consolidations.

Admittedly no private organization has the sheer magniture of the Federal Government, but on the other hand many of our corporations are larger than many Federal agencies, and many of their geographical facilities are larger than many Federal facilities. In this light, most of the study findings concerning the Federal Government can be, with proper translation, made directly applicable to many of our leading corporations. A particularly pertinent section appears on page 35 of Metron's report and suggests a recognition of the gravity of the problem and the necessity for management to face up to it and take drastic corrective actions:

> "It is obvious that calibration/repair facilities with their supporting standards laboratories are expensive to establish and to maintain. It is not so obvious to the non-metrologist that it is almost impossible to equip (or to staff) such facilities to exactly match the capability and workload requirements, hence, some degree of over-equipping and overstaffing are acceptable and commonplace."
>
> "Facilities with large average workloads and diverse technical requirements generally have less justification for over-capacitizing. However, wasteful and deliberate overkills are probably commonplace. These factors, compounded by total facility redundancy due to proliferation of these facilities by agencies all operating in close proximity to each other, are developing an enormous and somewhat unnecessary drain on the U.S. taxpayer."
>
> "A consolidation and amalgamation of these facilities on a predetermined geographical basis can considerable reduce this current financial drain. Because of the necessity to somewhat over-equip and over-staff the smaller and medium sized facilities, a unique phenomenon exists in the case when such facilities are combined; one plus one does not equal two ($1 + 1 \neq 2$), but rather some sum between one and two. Often a combination of three or even four still totals less than two."
>
> "Metron feels strongly that very substantial savings can be afforded by judicious consolidation of Federal Calibration/Repair facilities. A side bonus may also occur

in some instances in enhanced technical capabilities normally beyond the reach of some of the smaller and less affluent agencies. . . . ."

The recommended organization would reduce duplication of calibration activitives throughout the company. This is important as much of the above, translated by converting Federal references to "your organization" and "U.S. taxpayer" to "your stockholders", can fit non-Federal situations today.

Each of the subordinate organizational units should be mandated to perform according to detailed and well defined functional outlines and their recommended organizational structures. Suggested organizations and responsibilities are shown in Figures 2,3,4 and 5.

The General Maintenance Activity shown on the organization chart in Figure 2 is a unique but well proven method for reducing the non-technical, lower skill work loading normally placed upon the calibration and maintenance technicians. This activity can be responsible for all physical (versus functional) aspects. These people would concern themselves with such tasks as cleaning all incoming instruments, repairing cables, refinishing sheet metal cabinets, repainting and refinishing, performing major internal repairs as specified by cognizant technicians, building special calibration fixtures and the like.

This unit can provide a new career path for unskilled and semiskilled individuals not otherwise qualified to be part of a metrology organization. Such an activity currently does not exist in most calibration organizations, but where it does it is generally cost effective and profitable as well as a source of organizational pride.

PERSONNEL FACTORS

The balance of this paper will concentrate upon the personnel and organizational aspects of an effective Metrology operations properly qualified and managed personnel can handle the equipment and environmental factors as required.

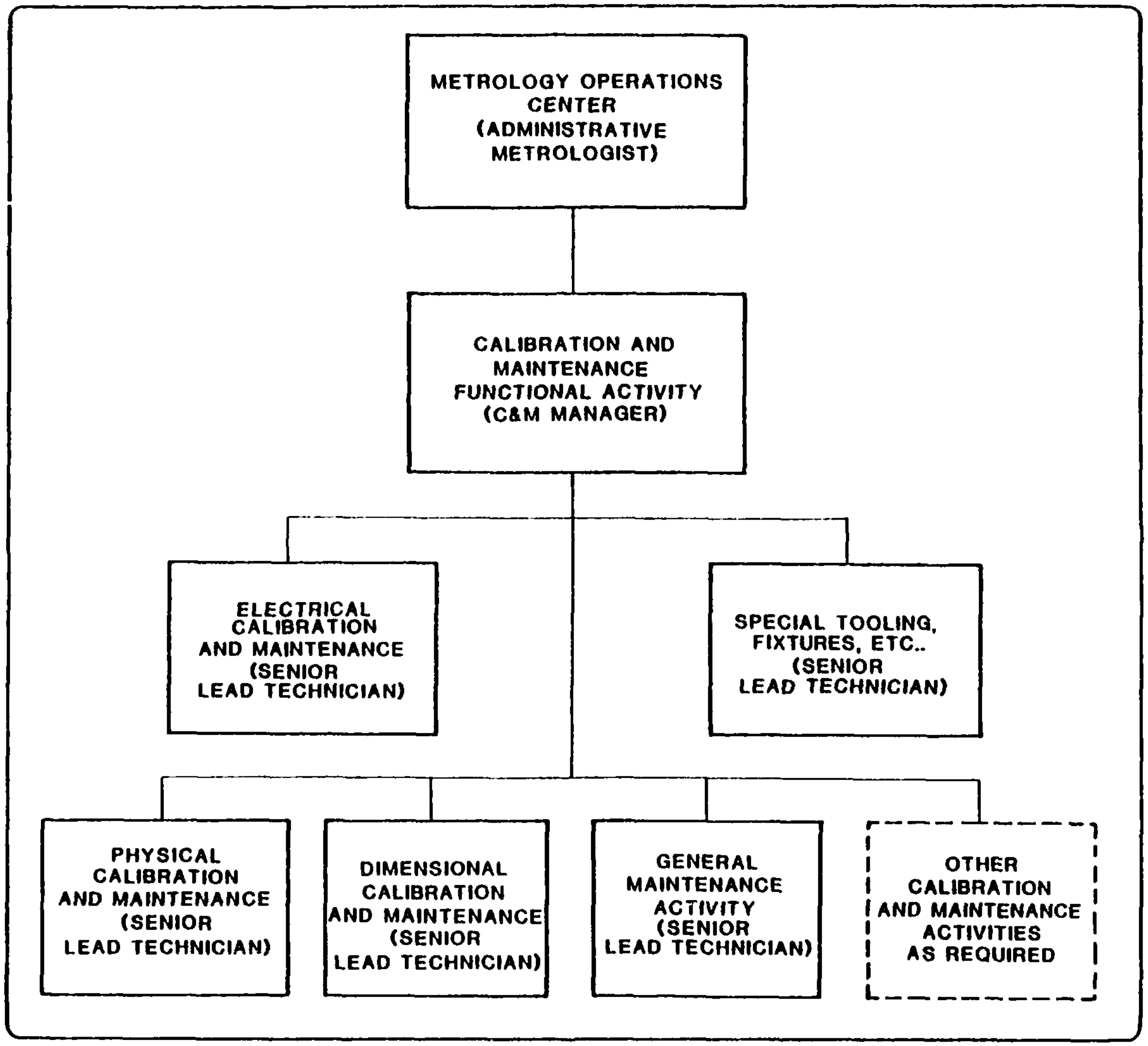

FIGURE 2
TYPICAL RECOMMENDED CALIBRATION AND MAINTENANCE ORGANIZATION

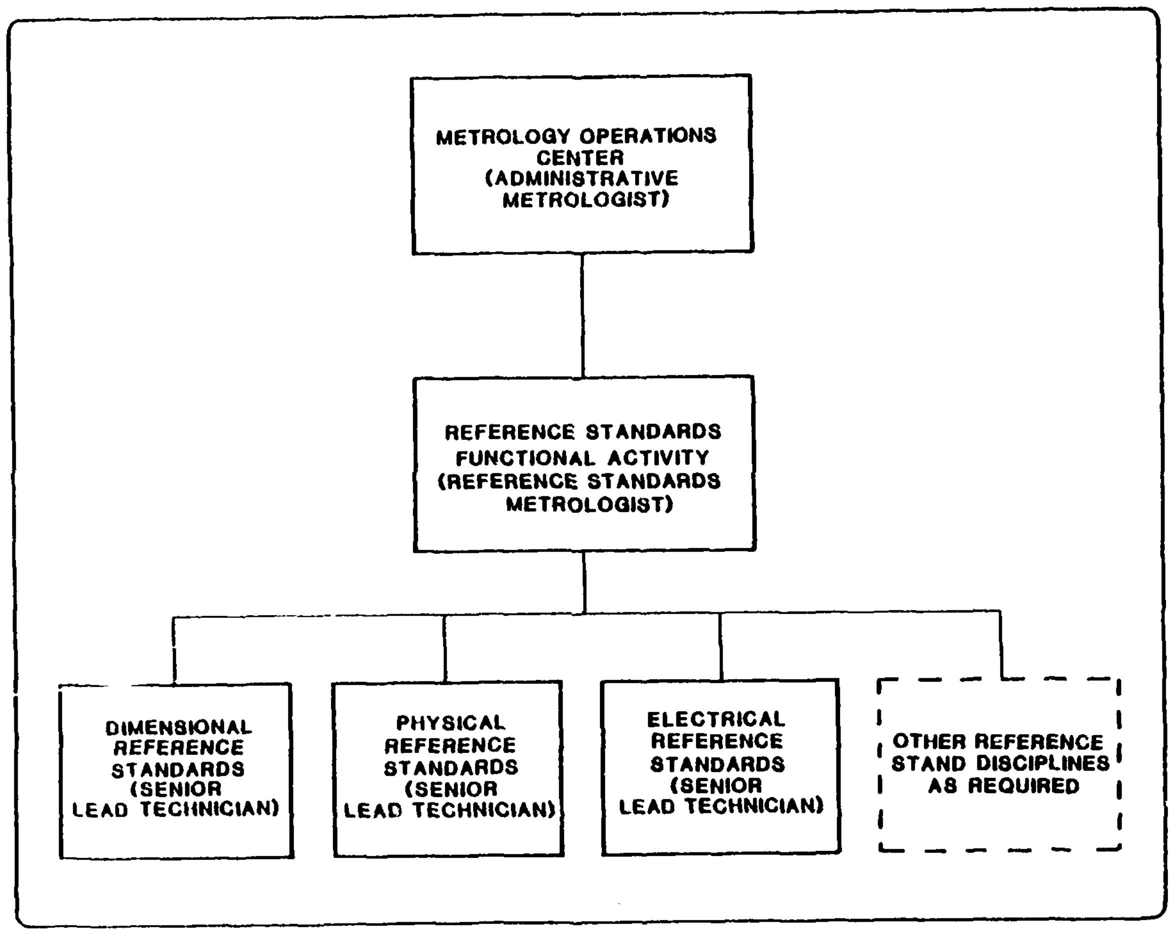

FIGURE 3
TYPICAL RECOMMENDED REFERENCE STANDARDS ORGANIZATION

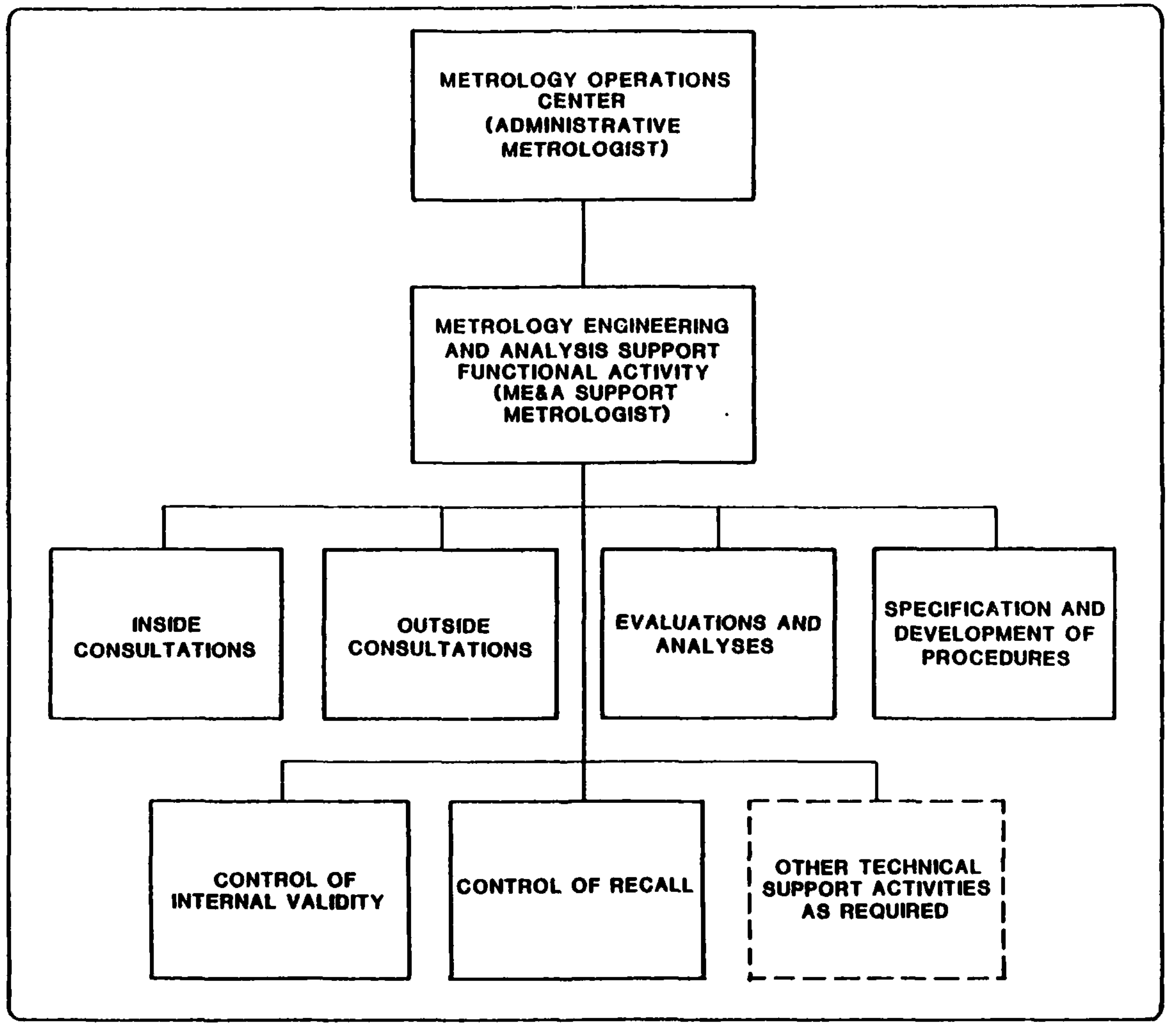

FIGURE 4
TYPICAL RECOMMENDED METROLOGICAL ENGINEERING AND ANALYSIS SUPPORT ORGANIZATION

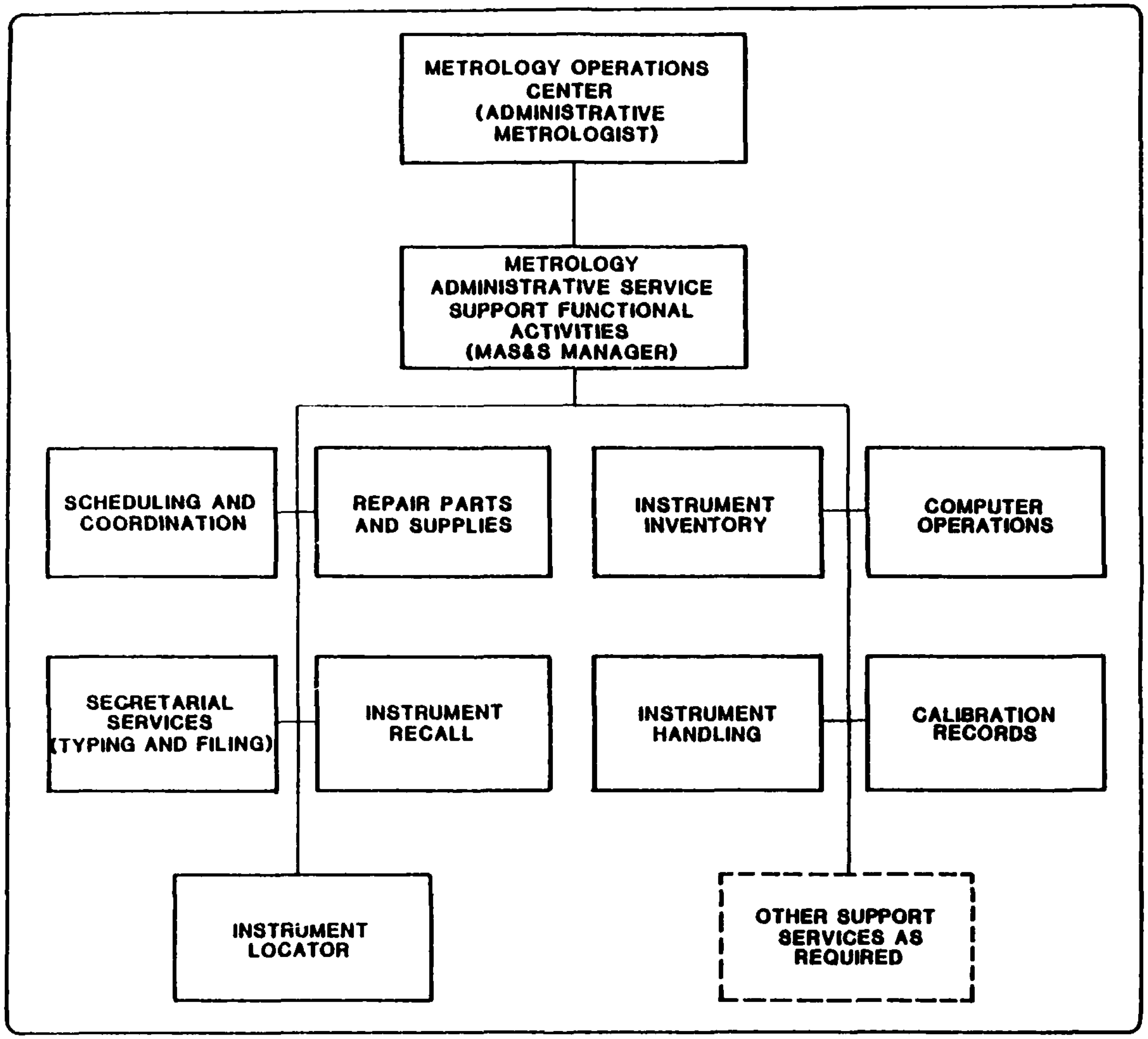

FIGURE 5
TYPICAL RECOMMENDED METROLOGICAL ADMINISTRATIVE SERVICE SUPPORT ORGANIZATION

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It is a well established axiom that no organization can succeed without proper personnel, particularly lead personnel. The very finest personnel may be able to function somewhat without an organizational structure, but their effectiveness certainly will be severely handicapped. But any organization, no matter how well conceived and implemented, is doomed unless it is staffed commensurately. Let us examine the qualifications for several of the key personnel necessary to staff this suggested Metrology Operations Center or Center of Metrological Competence, if you will. Also, let us draw a technical, personality, and psychological profile as needed, but with full realization that what we are developing is an ideal, a target which may never be totally achieved but one which should be continuously sought.

First, though, let us discuss a factor which is a common denominator throughout personnel selections for any competent metrology management and other key positions. That factor is professionalism.

The lack of recognition by some management that certain functions must be lead by technically competent professionals is a problem source common to several technological areas including Metrology. Definition of the problem is difficult because professionalism itself is extremely difficult to define.

Professionalism is a characteristic which normally cannot be instilled into an individual. Occassionally it maybe, but generally one is born with it. However, being born with it does not guarantee that it will be developed and brought out. Too often the public confuses education with professionalism, but the world has many highly educated non-professionals as well as a fair share of highly developed professionals whose formal education is minimal or even non-existant. Basically a professional must be totally dedicated to what he is doing, totally competant to do it, and totally aware of his own capabilities and limitations. He must possess total moral and ethical integrity and be strong enough to resist unethical actions irrespective of consequences. Equally important, he must be recognized as a professional by his peers.

Sometimes, in well meant but poorly directed efforts to alleviate these kinds of problems, engineers are transferred to the Metrology staff. Simply adding an engineer to the metrology staff usually does not solve professionalism problems. Instead it simply costs the organization a good engineer elsewhere.

In addition to professionals manning the key positions in a metrology organization, para-professionals are also required. Para-professionals are individuals who are highly developed technologists customarily working for and with professionals and para-professionals form a team dedicated to the objectives for which they have been trained. They live, think and function

as a team, each member respecting and relying on the other for his performance in the area in which he is skilled and trained.

Everyone cannot be a professional metrologist any more than everyone is equipped to become a professional physician. Teams of physicians with their para-professional nurses, nursing assistants, orderlies, "candy stripers" and so on are commonplace within the medical field. In metrology we require the same structure, i.e., a professional, possibly assisted by one or more other professionals, directing and inspiring a team of surrounding para-professionals.

Removing the professional from his position of leading and continously inspiring the para-professionals can initiate extreme long range deleterious effects. The para-professional and technicians will have, as a result no leadership of their own kind, no fountain head of inspiration, no touchstone of integrity, no wellspring of technical counsel (we suggest the reading of Millers[15] monograph on the subject of professionalism in quality control for another but similar viewpoint on this subject).

<u>The Administrative Metrologist</u>: A Metrology operation, as pointed out above, must be headed by a professional, in this case a metrologist or, more specifically, an <u>Aministrative Metrologist</u>. This requirement is not unique. For example, who would entrust himself to a hospital headed by an accountant? Or to an engineering school headed by a lawyer? Many operations of a technical, manufacturing or other hardware-related nature can be more or less successfully headed by business school trained managers who are not competent in the technologies or manual skills that they are managing. Like the hospital and the engineering school, metrology is not one of these.

Metrology top manager must have at least a minimal competence, and be throughly conversant in all of the disciplines and technologies that he is expected to manage. Generally speaking, it is not possible to take technicians, senior or otherwise, and train them into becoming metrology managers. In most cases the professionalism is not there. Again, in doing so you have not gained a metrology manager, but rather probably lost a superior senior technician. Effort would be much better spent in developing that person into a super-technician, craftsperson, artisan, or para-professional.

The metrology manager or administrative metrologist is personnally responsible for the propriety of every measurement made by his subordinates. Indirectly he is, and rightly should be, totally responsible for the correctness and adequacy of all measurements - not only in the metrology function but in the plant as a whole.

The professional integrity of the metrological manager must be such that he automatically can assume total responsibility for all

work performed under him, and at the same time instill some of this same attitude in his subordinates -- the same subordinates who may have bungled the very measurements for which he is taking the "blame".

Calibration and Maintenance Manager: The qualifications for the Calibration and Maintenance Activity Manager are quite a different matter from those of the Metrology Manager. This individual should be one with long experience in working with the equipment and with the type of people involved. He must have been a para-professional of long standing and of recognized stature on the one hand, and on the other, he must be one of those rare para-professional individuals who also possesses that germ of professionalism which can be developed. He must be respected by his subordinates as well as his superiors and his peers. Above all, he must be both a leader and a disciplinarian. He definitely must be one who can lead and inspire both discipline and loyalty at the same time. This combination will usually dictate that the individual has come up from the ranks.

Reference Standards Metrologist: In most organizations this slot is too often filled by a Senior Technician with long experience in the organization and with the specific items of standards hardware which he is expected to maintain. But in doing so there is a strong risk of deterioration.

Most internal operating systems in metrology, particulary those of an advanced technical nature, require continual systematic maintenance and upgrading. There is an old adage which says, "Familiarity breeds comtempt". A corollary might be derived from this: "Rote repetition breeds ill-advised shortcuts." This is precisely what has happened to many organizations which have been deprived of a professional metrologist monitoring and supervising the system. The para-professionals, unknowledgeable of the "whys" at the roots of the systems and procedures, frequently modify them (and usually with the best intentions). The results invariably are a slow deterioration of the measurement assurance system. While this is true for all of the systems in Metrology, it is particularly true in Reference Standards and is more difficult and expensive to repair.

It is probably necessary in such cases to locate an experienced Reference Standards professional with supervisory potential and to depend upon him to establish the Reference Standards Laboratory under the general guidance and direction of the Administrative Metrologist.

The minimum ideal qualifications required for such a Reference Standards functional head are as follows:

1. He must be thoroughly familiar with the "classical" methods of Reference Standards practice in all disciplines. Conversely, he must be thoroughly aware of the progress being made in the state-of-the-art and will continue to stay currently informed. No one forever lives in the past or upon the accomplishments of giants of yesterday. He must be eager and able to evaluate, accept, and implement new developments when and if they apply to the organization needs.

2. He must intimately know and have contact with the leaders of today's metrological profession. This requires established communications with these leaders and enables evaluations of them and their work.

3. He must be thoroughly qualified in physics and mathematics - the basic sciences underlying Metrology.

4. He must know the equipment of today's Metrology - the advantages and disadvantages, the capabilities, and the limitations of particular items. Of equal importance, he must understand the principles upon which each item operates. Only through this knowledge can the organization avoid costly mistakes and buy the most for its equipment dollar.

5. He must understand the relationship between statutory requirements and contact requirements on the one hand, and the implications and limitations of certificates and standards on the other.

6. Of paramount importance to a cost effective operation, he must readily recognize the delicate balance, economically and technically, between the difficult and/or the costly improvisation, and the expedient but also costly specialized equipment

Metrological Engineering and Analysis Support Head: Here we have a spot for a metrologically experienced professional who is more attuned to analytical and developmental approached rather than to hands-on-the-hardware calibrations or to standards maintenance. As in the other supervisory positions, supervisory potential is a must. The minimum requirements for this individual are much more manifold than for the other activity heads because of the broader range of responsibilities for which this organization is responsible. In fact, qualification for a proper individual to optiminly fill this position are far too lengthy to completely delineate here. But since he will be leading a high technology organization, he must be able to assume responsibility for the general directions or methods to be followed.

He must wisely and rapidly evaluate these proposed methods and directions in terms of correctness, validity, rapidity, convenience and reliability.

These factors must always be viewed by him with respect to these questions: "Is it in the best interests of the company?", "Is the cost reasonable, minimal and justificable?", and "It it proper for the Metrology organization?".

He must be capable of assuming responsibility for consultations within and outside the metrology organization, specifying the technical procedures to be used within metrology and controlling the internal validity of all tests and calibrations.

He must be professionally capable of recognizing that he coordinates the organizations technical conscience and of displaying and exercising an unusual depth and degree of independent, sole judgement which can only be based upon a high degree of maturity combined with experience in depth.

He must strike a balance between safety (in measurement assurance) and economy with full knowledge that absolute assurance (safety) costs infinite dollars; he must be capable of directing and performing rapid but meaningful statistical analyses, yet being fully cognizant that statistical results alone can be dangerously misleading. Finally he must be constantly aware that good and extensive technical documentation and extensive technical records are the only base upon which to erect a structure of metrological statistical analysis, which in turn, provides a means of estimating the quality risks for which he and the Administrative Metrologist are responsible.

Metrology, as in many rapidly advancing fields often requires judgement born of experience. This is sometimes properly expressed as "expert opinion" and improperly as "educated guesses". The professional heading the Metrology Analysis and Engineering function must assume the position of coordinator of the Metrology organizations group "expert opinion". To accomplish this he must possess an established reputation. The exercise of such judgement reside in the expertise and experience of the individual making the judgement and, more particularly, in the group leader himself. Even if this leader has remarkable capability, he may well be quite ineffectual and unbelieved unless he has also gained an established reputation.

A parallel to this can be seen in decisions required of economists. Action on economic decisions must often be taken on an individuals reputation rather than on rigid proof.

<u>Metrology Administrative Services and Support Head</u>: The qualifications for the ideal head of this organization are also unique, but not as extensive nor exacting as those described above. The

ideal candidate should be at least a para-professional with a background in documentation, records, organization, procurement, and data processing. He should have technical experience in instrumentation and be conversationally fluent in the field. An orderly mind and a fetish for meticulous recordkeeping are musts. In addition, an even more important attribute is the ability to interface effectively and amiably with people, both within and without the organization. Some legal background or formal law schooling is also often an advantage.

MORALE FACTORS

Another major area of importance in any properly operated service organization is the mental attitudes of the people involved. This includes not only their morale, but also their outlook concerning people and things outside of the metrology function. Here, as in most organizations, morale is basically a function of confidence and admiration for the most immediate levels of management.

As stated above, the manager is rightly or wrongly totally responsible for everything that happens. This view is particularly held by subordinates. Realistically, though, the immediate managers responsibility is often usurped by higher-level policy and management. But he must be continously fighting for his subordinates causes. They want a "St. George slaying dragons" even if he turns out to be a "Don Quixote jousting windmills". For example, the para-professionals may need to, on occasion, see their immediate management "shot down in flames" over issues affecting metrology well being. This is particularly true when unfavorable decisions are made at such high management levels as to be impossible for metrology management to contest effectively. However, they should support their subordinates position by contesting it to the bitter end. The recognized professional metrologist goes a long way to win these battles. That is how one can really build confidence and morale in the organization.

As for the attitudes between the personnel of various calibration and standards units comprising the overall metrology function, in many organizations they too could withstand some redirection. An oversimplification of the negative attitudes which sometimes exists between the personnel of the component elements of some organizations can be exemplified by such remarks as follows:

> From the Calibration side: "Those guys across the street are living in an ivory tower vacuum".
>
> From the Standards side: "Why don't those cal lab guys blow away so we can concentrate on doing interesting jobs for the rest of the plant?".

The point must be constantly made and sold by Metrology management both inwardly and outwardly that the total Metrology Function is and must be a team effort. Support of the Calibration and Maintenance Functions is the only reason for the teams existence, and the Standards Laboratories and the Support Service Functions can justify their existence only in the support of the Calibration Activity. Continually remaking that point is a prime first-level management responsibility. The entire Metrology organization personnel must be made to feel proud of their organization and of their joint achievements.

The total metrology staff must be made to recognize their extended relationship to those outside of the metrology organization. The worst attitude of metrology personnel toward their outside customers which this author has witnessed occurred during an audit. Two individuals came into the instrument service area asking for advise. They apparently were from some type of a manufacturing or tool engineering function. They had a problem involving instrumenting an upcoming manufacturing process. They had done their homework well and were very fluent in expressing their needs. They had figuratively come "hat in hand" asking for advise and recommendations of commercial devices and sources for the instrumentation they required.

We witnessed what we considered very shabby treatment of these individuals by the metrology personnel present. How the visitors were able to maintain their cool and polite demeanor was difficult to understand. Things came to a climax when one of the metrology personnel said, in effect, "It is none of our business here in Metrology to help you find instruments for tooling purposes. Go find your own items, and when you get them, turn them in to us and we will calibrate them. We will then tell you if they can do the job you require." At this point this auditor could restrain himself no longer and stepped in and advised the visitors who, upon receiving the advice sought, they left happy.

The point is that it is everybody's responsibility in any company to help design, manufacture, and sell products. The only difference is that some individuals are more responsible for certain phases than others. Everybody is responsible to help everybody else to his job. Metrology is no exception. It is a service organization in existence solely to support the rest of the facility. Metrology personnel must be made to understand this and should act accordingly. The responsibility for this lies directly upon the professionals heading the Metrology organization.

DEVELOPING A METROLOGY OPERATION

In developing a Metrology organization the initial step is to acquire the services of an eminent metrologist. For small organizations that type of service can be obtained on a consulting

basis with a retainer contract. A professional metrologists presence alone can solve many morale problems in addition to technical ones.

The next step is to institute internal training for all metrology personnel, including management, not only in technical aspects of the organization but in the organizational and service aspects as well. Teach them to understand what it is to be part of a metrology team. Make them realize that the entire effort exists only to serve, to maintain and to calibrate the instruments used by manufacturing, engineering, quality control and plant maintenance, and that in doing so they become full partners in the production, quality, and design efforts. Teach them that the Reference Standards Laboratories exist only to support the calibration effort, and they can never be allowed to become an "Ivory Tower" dedicated to their own ends. Condition the Support Service personnel to the knowledge that they exist solely to provide service inwardly to the Metrology function and outwardly to the rest of the facility, and that they are responsible to provide that service when and as required, 24 hours a day if need be, not just at their own convenience!!

An important step in the initial stages of development is to initiate formal technical training programs for all metrology personnel at all levels. Remain cognizant of all sources of training, i.e., college and universities (both full-time and night courses), NBS and other specially designed seminars, self-study and correspondence courses, and formal on-the-job training.

It is important that any training resource fit the needs of the individual as well as the organization. Keep in mind that it is unlikely that the needs of any two individuals are precisely the same, i.e., the program must be flexible.

Get the organization active in Metrology related trade associations and vigorously encourage metrology personnel to join and become active in these. These activities naturally take two forms: (1) trade associations for the organization, and (2) professional societies for individuals. A few such organizations are hybrid and permit both individual and company memberships. Some of the Metrology related Trade Associations are: The National Conference of Standards Laboratories (NCSL); The Government-Industry Data Exchange Program (GIDEP) - Metrology Committee; and the National Conference on Weights and Measures (NCOWM).

Professional Societies include: The Precision Measurements Association (PMA); The Instrument Society of America (ISA) - Metrology Division; The Instrumentation and Measurement Society of the Institute Electrical and Electronic Engineers (EMS-IEEE); The American Society for Quality Control (ACQC) - Metrology Division and The Precision Measurements Society (PMS)

SUMMARY

In summary, let us reiterate several key points. Others have demonstrated that:

1. Productivity, quality and profitability are functions of the certainty of the measurements made during the conception, development and manufacture of a product.

2. The certainty of a measurement is, among other factors, dependent upon the accuracy of the measuring tools used at the time of their use.

3. Proper planning, programming, and periodic recalibrations are essential to measuring instrument accuracy.

This paper proposes that:

1. Calibration is the key and essential component of an overall quality program and is a component of the overall metrology program. There are totally interdependent, i.e., they depend upon each other for existance. Calibration cannot exist and function efficaciously without adequate support from the other metrology service functions - Reference Standards, Metrology Engineering and Metrology Services. On the other hand, these services have no reason to exist except to service the Calibration effort.

2. The three essential elements of any effective metrology program are personnel, equipment and environment, in that relative order of importance.

3. Personnel must be properly organized, motivated, trained and managed to be effective.

4. Metrclogists can be effectively managed only by a professional Metrologist - An Administrative Metrologist, i.e., an individual personally and technically compident in all of the sciences, technologists, and crafts under him as well as skilled in the crafts of administration and the art of managing.

5. Subordinates must be professionals or para-professionals.

6. To function effectively these Metrology personnel must be properly organized with all organizational responsibilities converging on the Administrative Metrologist.

7. Finally, all of the above together constitute inseparable requirements for an efficient Metrology Organization.

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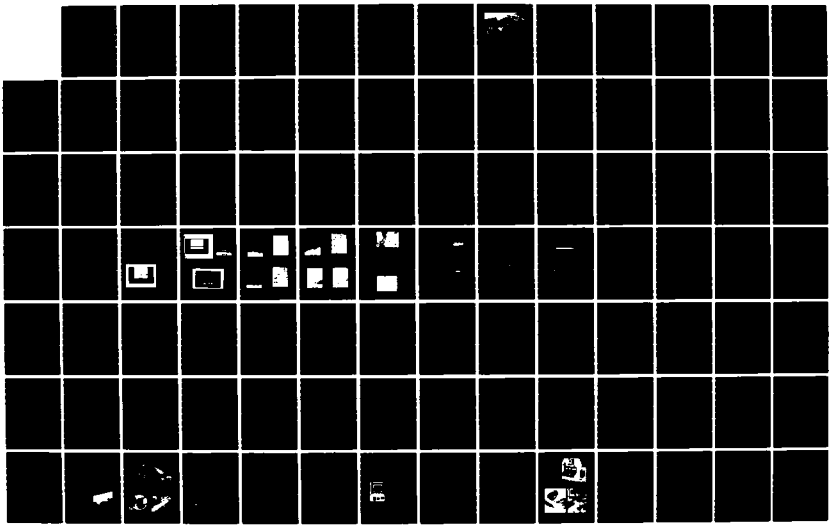

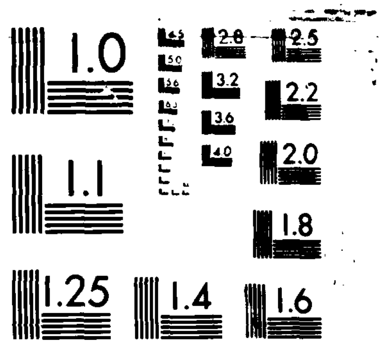

MICROCOPY RESOLUTION TEST CHART

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9

Cleaning Printed Wiring Assemblies with Isopropyl Alcohol — an Attractive Alternative to Conventional Cleaning Solvents

By Scott Goepfert
Honeywell Inc.

The reliability of modern, electronically sophisticated weapons is, to a considerable degree, dependent on the cleanliness of the individual printed wiring assemblies (PWAs) they contain. Ionic residues left on the assemblies by poor cleaning processes can cause both electrical and mechanical failures under the severe environmental conditions frequently encountered by the Military. All efforts to produce reliable solder joints are useless unless we make certain that our cleaning process is thorough and meets or, preferably, exceeds the requirements of MIL-P-28809.

Conventional Cleaning Methods

Two primary methods are presently used to remove post-soldering rosin fluxes from PWAs. Dissolution is the most popular and involves the use of solvents to dissolve contaminants and carry them away from the assembly. Another method, saponification, is a fast-growing newcomer to the electronic industry. It uses alkaline detergents that chemically react with contaminants to form soap-like compounds which can readily be washed away with water.

Both cleaning methods have certain drawbacks which must be considered carefully.

Dissolution

Dissolution requires application of a solvent for dissolving flux and oils from circuit board assemblies after—and possibly before—solder operations. Because contaminants are both ionic and nonionic, these solvents must be capable of holding both types of substance in solution. To achieve this, blends and azeotropic mixtures of polar and nonpolar fluids have been developed.

Most commonly used solvent mixtures consist of alcohols as the ionic vehicle and halogenated compounds, such as 1,1,1-trichloroethane and 1,1,2-trichloro-1,2,2-trifluoroethane, as the nonpolar constituent. Although these solvent mixtures are convenient because of their nonflammable nature, they also have some less desirable characteristics.

Solvent Composition Control — One inherent problem with halogenated solvent blends is the depletion of the polar solvent when water is introduced into the system. This is a common occurrence when vapor degreasers are employed because water condenses out of the ambient air around the solvent vapor condensing coils and mixes thoroughly with the solvent in the holding reservoir. Because alcohols, for instance, have a greater affinity for water than for the nonpolar constitutent of the blend, they are scavenged by water and lost through the water separator of the vapor degreaser. This is critical since the alcoholic part of the solvent blend is the only constituent capable of removing ionic contamination. Although this phenomenon can be controlled by using desicant driers and minimizing chilled water temperatures, it can also be an expensive and difficult process to control, especially in a factory that protects against electrostatic discharge by maintaining a high relative humidity in the working area.

Health and Environmental Concerns — During the last several years, both government and private agencies have voiced concern over health problems related to halogenated solvents. A few have been documented as being mutagenic and possibly carcinogenic. Most tests performed with these solvents are inconclusive, but enough information has been uncovered to warrant further investigation.

Environmental concerns about halogenated solvents are primarily related to the suspected photochemical reactivity of fluorocarbons with the ozone layer in the stratosphere. Although this process is strictly hypothetical, the catastrophic consequences of the theory have prompted government agencies to develop stringent regulations regarding their production, use, and disposal until more research is performed.

Steadily Rising Costs — Halogenated solvents are relatively expensive, ranging in price from approximately $5.50 to $12 a gallon. Some of the solvent cost is recoverable by selling spent solvent to reclaiming agencies, but fees of as much as $250 a barrel can be charged to dispose of waste that is not reclaimable. Proposed governmental regulations and a noticeable market shift towards aqueous cleaning are causing halogenated solvent prices to rise steadily.

Water Wash Systems

Removal of rosin flux with an aqueous cleaning system requires use of alkaline detergents to chemically react with the rosins, turning them into the soap-like compounds that are washed away in rinse stages. This type of cleaning, like dissolution, presents certain problems.

Corrosion and Solution Entrapment — PWA designs with densely arranged components and close board-to-component clearances present serious problems for aqueous cleaning systems when rosin fluxes are being removed. Alkaline solutions used in the wash stage of water wash systems are both conductive and corrosive in relatively low concentrations. Entrapped wash solution which cannot be removed in subsequent rinse stages poses a greater threat to hardware function than the flux contaminants being removed.

Environmental and Cost Concerns — Environmental concerns about aqueous cleaning systems primarily involve disposal of wash solutions. In some cases where factory sewer disposal is minimal, wash solutions must be treated in on-site facilities for pH and lead concentrations prior to final disposal. Concentrations of lead in excess of 1 ppm at the building sewer exit will commonly violate many city regulations.

Basic PWA Cleaning Analysis

Because of our dissatisfaction with both cleaning systems, we at Honeywell's Underseas Systems Division, began an extensive research program to develop an optimum cleaning process. We selected PWAs from the Mk 46 torpedo to use as our test hardware and concentrated primarily on cleaning rosin fluxes. Preliminary studies concluded that there is a definite equation for success which involves the following variables:

- PWA design
- Soldering process
- Cleaning process

By examining these variables closely, it can be determined that the cleaning process is entirely dependent on the first two variables. Our tests also showed that, of the three vaiables involved, the first, PWA design, was the major contributor to the cleanability of the PWA. For obvious reasons such as military requirements and redesign cost, we decided to leave the PWA design fixed and adjust the last two variables as necessary to attain cleanliness standards which exceeded MIL-P-28809 requirements without degrading soldering. Cleanliness testing was performed with the Kenco Omega Meter.

After extensive testing of several water wash systems, varying soldering and cleaning parameters systematically to enhance cleaning, we concluded that the saponification approach was incompatible with our test hardware. Rejections were primarily due to entrapment of alkaline wash solution under densely arranged components and in connector casings. When the concentration of detergent in the wash stage was reduced, the entrapment problem decreased, but flux residues were then visible. Some component markings did come off, but the problem was easily resolved by using a different ink.

Comprehensive tests were then performed with batch and inline vapor degreasers using three popular halogenated solvents. Once again, the remaining cleaning and soldering parameters were systematically varied to enhance cleaning. Cleaning was adequate with each solvent in both types of vapor degreasers, but cleaning parameters varied dramatically among the three solvents used. Although our halogenated solvent cleaning tests were favorable to a certain extent, no easy solution was apparent to the problems of the health and environmental concerns, solvent composition control, and steadily rising costs of purchasing and disposing of halogenated solvents.

Isopropyl Alchohol Water Azeotrope — a Feasible Solvent Alternative

Throughout our experimentation with various cleaning methods, a mixture of 75% isopropyl alchohol and 25% water was used to remove residues of rosin, activators, and saponifiers left behind in the cleaning process. A closer look at this solvent mixture revealed that it has been used for years in hand cleaning operations and is commonly used in fluxes to keep rosin and activators in solution. In fact, the Kenco Omega Meter we used to detect residual ionic contamination uses a 75% IPA, 25% water mixture to dissolve contaminates for subsequent resistivity measurement. Simple laboratory tests showed that the IPA/H_2O mixture at room temperature was indeed nonpolar enough to remove rosins and body oils, etc., while polar enough to scrupulously remove all ionic contamination. Further testing with boiling solvent showed cleaning results which far exceeded those of the halogenated solvents, both in cleanliness and rate of cleaning. Finally we tested the azeotrope of IPA and H_2O which consists of 88% IPA and 12% water, and, again, excellent cleaning was evident.

Our feasibility study left us with the following conclusions:

- The azeotrope of IPA/H_2O worked nicely as a vapor degreasing solvent. It has a boiling point of 178°F.
- The IPA/H_2O azeotrope is an excellent solvent for removing PWA contaminants. Tests showed a 20+ megohm-centimeter resistance for all PWAs tested compared to 11 for halogenated solvent under the same conditions.
- IPA/H_2O azeotrope is inexpensive, approximately $2.00/gal.
- Health and environmental aspects are favorable, better than halogenated solvents. Spent solvent can be sold as a secondary fuel in most cases.
- The solvent is flammable, with an upper explosive limit of 11% and a lower explosive limit of 2%; thus, conventional vapor degreasing equipment cannot be used. However, specially designed equipment could be built to use the solvent safely.

IPA/H_2O Cleaner Design

With data obtained from previous water wash and vapor degreasing tests, we designed an inline solvent cleaner that could use the IPA/H_2O azeotrope (see Figures 1 and 2). The actual size and type of stages used in the cleaner were developed from experiments done with a small-batch vapor degreaser. Our final machine design consists of the following cleaner stages:

- Cleaner entrance—solvent vapor barrier, 66 inches long.
- Boil sump, 66 inches long.
- Recirculated spray section, 30 inches long.
- Final rinse spray section, 12 inches long.
- Cleaner exit—solvent vapor barrier, 66 inches long.
- Solvent blow-off, 75 inches long.

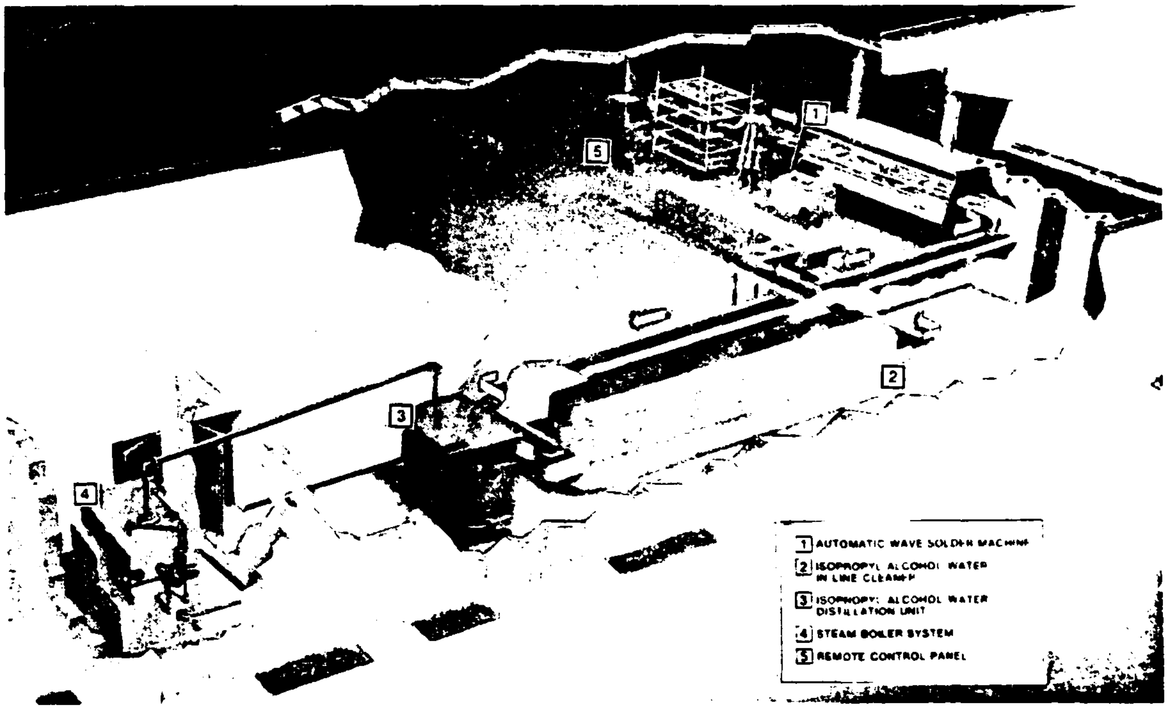

Figure 1. Advanced Wave Solder and Cleaning System.

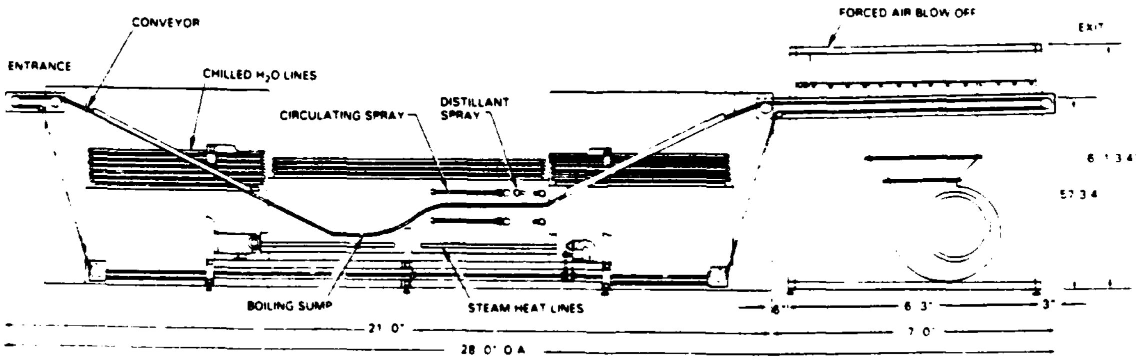

Figure 2. Isopropyl Alcohol/Water In-Line Cleaner.

The cleaner operation is actually very simple. The operator loads parts to be cleaned on an input conveyor from outside the cleaner room. Parts transfer from the input conveyor to the flighted stainless steel mesh conveyor of the cleaner automatically. PWAs then descend at a slope of 30 degrees through a solvent vapor barrier into the boiling sump section where they travel submerged in the boiling liquid. Here the majority of the flux and other contaminants is loosened. A large amount is removed from the PWA by the boiling agitation.

The PWAs then ascend at the same slope into the recirculated spray section where 150°F solvent is sprayed on both the top and bottom sides of the PWA at a rate of 70 gal/min at 10 psi. Flux and contaminants loosened in the previous stage are removed here. The PWAs then travel through a final rinse section where pure distillate solvent is sprayed on both the top and bottom of the PWA at approximately 50 psi and a rate of 1 gal/min. The PWAs finally ascend at 30 degrees through the vapor barrier and enter the blowoff section.

Any solvent remaining, entrapped under ICs and other components, is physically removed by a recirculated-air jet which moves 6500 cfm of air at 110°F down on the board. Any solvent removed at this stage is exhausted out of the building. Clean, dry PWAs then automatically transfer off the cleaner conveyor to an exit conveyor which transports the parts back to the operator's station for unloading. The solvent system is maintained by a 120-gal/hr still. The entire cleaning system holds about 230 gallons of the IPA/H_2O solvent.

IPA/H_2O Safety Precautions

Because of the hazardous nature of IPA, several safety precautions were taken in the design of this experimental cleaner:

- The machine was designed to meet Class 1, Division 2, Group D, requirements of the national fire code. All solvent heating is with steam, and cooling is with chilled water.
- A special explosion-proof room was built to house the machine and spare solvent (meeting Class 1, Division 1, Group D, requirements).
- A unique fire arrest system was installed which can rapidly detect and extinguish any fire in the cleaner or the room.
- An IPA vapor monitor was installed to audit IPA vapor levels in the room and shut the system down should the lower explosive limit ever be approached.

- The entire system is controlled remotely so cleaner operation is performed from outside the explosion-proof room.

- Controlled access to the cleaner room allows only trained personnel to enter.

With these design precautions, we were able to secure project approval from the Honeywell Safety department, the city fire department, and the Industrial Risk Insurance Company.

Project Results

Project results are very encouraging. Cleanliness tests on the same test hardware after using several RMA fluxes all passed with 20+ megohm-centimeter resistance in the Omega Meter test. Conveyor speeds were raised to 10 ft/min with little change in PWA cleanliness. Several RA fluxes also passed with slightly lower readings when subjected to the same tests. Solvent loss is far less than expected—about 3 gallons per 8 hours of operation. The majority of the solvent is primarily through component drag-out.

Project Cost

Project costs were as follows:

• IPA/H_2O cleaner system		$ 70,215.00
• Cleaner building and hardware		167,924.00
	Total	$238,139.00

• Estimated savings in solvent costs over 12 months		$12,480.00
• Estimated savings in labor costs over 12 months		62,730.00
	Total 12-month savings	$75,210.00

- Rough payback = 3 years

Labor and solvent costs are figured at the current Mk 46 Torpedo production schedule. Projected production increases will reduce the payback period substantially.

Conclusions

In conclusion, the IPA/H_2O cleaning system is extremely effective at removing common contaminants from PWAs. The IPA/H_2O azeotrope is very inexpensive and has better health and environmental characteristics than halogenated solvents. Isopropyl alcohol can be used safely as a cleaning solvent when necessary safety precautions are taken, but it should never be used in conventional cleaning equipment that has not been designed for flammable solvents. During the design, development, and implementation of the IPA/H_2O cleaner system, several items were uncovered which could reduce project costs substantially in the future. The isopropyl alcohol/water azeotrope offers an attractive alternative to conventional cleaning solvents.

A special thanks to Art Gillman and Will Foster from Unique Industries for their help in the development, design, and manufacturing of the IPA/H_2O in-line PWA cleaner.

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QUALITY ASSURANCE

COST DRIVER OR COST SAVER

BY

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QA - COST SAVER OR COST DRIVER

My objective is to show that the Quality Assurance function is a cost saver, and to present the real cost drivers and their causes.

I am going to redefine the terms Quality and Quality Assurance as used throughout this paper somewhat differently than those we are accustomed to seeing or using. I shall define quality to mean "Conformance to Requirements" or "The ability of a product or item to perform it's intended function." The terms quality assurance, quality systems and quality function are synonymously used throughout my presentation and are defined as " A system of actions performed to assist in the establishment of adequate technical requirements and to preclude the manufacture of nonconforming products". The terms item or products pertain to commercial items, Government procurement items or complex weapon systems.

The examples used in this presentation have been sanitized so as to not embarrass any contractor or program office and for security purposes.

There are many other examples that could have been used, but those chosen represent a reasonable cross section of collected data.

As I was growing up I always heard the old cliche', "They just don't seem to make products like they use to", and in most cases the cliche' is still correct today. Due to the rapid advancement of technology and the increase in product

complexity, the requirements that must be imposed on the processes that impact the reliability and quality of the product both during the design and manufacturing elements have become more and more critical.

However, one of the biggest problems associated with producing a quality product is management attitude. Management attitude is one of the major cost drivers.

In one of Dr. Juran's articles he stated that 85% of the quality system faults are related to management attitude and 15% are attributable to the man and machine relationship.

The problem in a quality system and in quality management is "Not what people don't know about, it is what they think they know." If an effective quality system is to be practical and achievable it must start at top management. If top management doesn't engrain quality into the organization it will never happen.

If there is a lack of formal quality policy the personnel will make their own policy as individuals. Even though some company and Government management personnel know how to do the job, they are slow to change because they reject change and newness. Government and company management treasure the methods that have been successful before, not taking into account the advancement in technology and that their actions may cost the company and the Government a considerable amount of money as well as create a negative impact in the reliability of the product.

Several years ago I was asked to serve on a NAVMAT "Tiger

Team" to investigate a Navy system. Our findings and recommendations, which were many, were submitted to NAVMAT and the applicable Government and contractor program offices for action. Recently several of my associates were assigned to investigate problems on the same system at the same contractors' facility. Their findings to date reveal that many of the same problems found two years ago still exist. Very little progress or change was made during the two-year period.

We have learned to live with what we consider acceptable quality levels and when we establish the fact that nonconforming materials are going to be produced before we even start the job, we are basically saying that the production of nonconforming items is acceptable.

We also have company and Government management personnel that take the attitude of "Lets do the job just enough to get by", After all whatever system we're going to need to develop and produce a quality product, is going to be one of our biggest cost drivers and will cause us to miss our schedules".

Let me cite an example of management's attitude and the impact of that attitude. One of the programs I have recently been associated with has a contractual requirement that the equipment be produced to WS6536 soldering requirements. We asked the prime contractor to provide us with an estimate of the costs to set up a WS6536 capability both in-house and at his subcontractors. All of the companies involved have soldering programs which meet MIL-STD-454 and/or MIL-S-45743. The estimates from the companies' whose management attitude was

not adverse to the use of the specification, presented estimates which were within the range of the Government estimate for which, I might add, we have substantial data for back up. Those companies which were adverse to the use of the specification, presented estimates 60 to 140 times the Government estimate.

It is shameful when we manufacture our electronic games using better soldering and QA techniques than some companies' want to use on vital military hardware. Atari's new line of video games are being built to most of the requirements delineated in WS6536.

It is surprising and unfortunate that management still continues to think this way. Whenever I am around management personnel, quality costs have and will continue to be a topic of discussion with little desire to institute changes in the discipline and techniques that are required to assure the manufacture of a quality product at minimum cost. These managers have to be highly concerned with some aspect of product quality if they are to stay in the business or in their top management positions, but few are willing to commit the necessary up-front- money and to motivate lower level personnel to be innovative and to properly plan, document and implement a system to assure the quality of the product.

Management does not seem to understand that the establishment and implementation of an adequate quality assurance system not only saves the Government and contractors

money, but enhances their capability to meet the imposed and usually very tight schedules.

The same management that plays down the QA function either directly or indirectly, through omission or commission are the first ones to scream "We have a quality problem" when something goes wrong. And of course this is a common occurrence.

As you can see from the graph, QA is only one of the many elements of quality. The quality of a product includes the QA function, safety function, design, adequate parts and materials, adequate configuration management, reliability, manufacturing and other elements. To cohesively hold the elements together we must have adequate management and management participation. All of these functions must interface and work together to develop and manufacture a quality product.

The Quality assurance function must become involved at the earliest possible time in the acquisition cycle through tailored programs which take into account the acquisition phase, item complexity, quanity of items and the end item usage.

In the production process, which is mainly what I am discussing today, the function of an adequate QA system is to establish and implement the necessary procedures and methods to assure the prevention, early detection and immediate correction of any of the problems associated with the manufacture of nonconforming products. It is not these costs that are the cost drivers. The real cost drivers are: the

generation of unrealistic and unachievable QA and technical requirements, the rework, repair, disassembly, reassembly, scrap, software correction, inspection and retesting in the manufacturing arena, and the repair, rework, correction and shipping costs encountered on products and items in the fleet or in the commercial market. In addition, additional space and equipment is required to segregate and perform the work on the nonconforming items.

Recently I was involved in the review of a contractors' facility that fabricates a much needed item in our defense posture. a review of some of the records indicated that equipment was undergoing in excess of 200 hours test time just to get the bugs out and to gain confidence that the equipment would pass final testing. The hidden factory required for test, trouble shooting and rework was several times the size of the manufacturing area. The expense of the extra testing as well as the expense of trouble-shooting and rework was very excessive.

Several months ago I was tasked to gather Quality cost data from several major contractors that produce missile systems. These contractors were asked for trend data and the costs associated with rework, repair, reinspection, retest functions as well as their scrap costs. I was able to get the trend data but as yet have not been able to get adequate cost data because they do not know what the hidden factory costs of repair/rework/retest, etc really are. Most of the trend data obtained was biased because it only represented units presented for formal testing after undergoing manufacturing confidence

testing.

The lack of an adequate QA system is what drives quality costs so high. In addition, for commercial type items, dissatisfied customers will switch products and cause others to switch through personal discussions and bad publicity. This further costs the producer in profit from loss of sales. I think we can see evidence of this in the television market, the automobile industry and, in general, the electronic industry.

In the case of weapon systems and other Government procured items, additional costs are incurred because of the increase in paperwork, such as deviations and waivers, and of course we must also include the cost of reliability degradation. Other costs to the Government include the labor and travel of special teams that are required to audit and review the contractor who is having difficult problems, the reshipment of systems from the fleet to a repair depot, as well as all of the required paperwork. These costs are all relative to the design and manufacture of nonconforming products, not to the cost of doing it right the first time.

As Dr. Juran has said, "Regardless of the cost, it is always cheaper to do it right the first time." It seems that we never learn from past mistakes and we never seem to have enough money to do it right the first time, but always have enough money to bandaid the product and do the job over and over again.

One of the most difficult problems that I encounter during the procurement of DoD items, is to convince upper

management that the money for the establishment of a an adequate QA system must be up front. Even though the up-front costs may appear to be relatively high, it is money well spent because the up front money for the planning and establishment of a quality system for the product will be returned with interest.

Even though we plan an adequate QA system or we can make the necessary changes in an existing system the QA system and ensuring changes must be well thoughtout, they must be implemented according to plan and they must be constantly and consistantly monitored and reviewed. Most of the QA money is spent fighting fires and going from crisis to crisis and not in the prevention of the crisis in the first place. Unfortunately some of this country's top management personnel attained their positions because of their ability to handle crisis problems and to manage the crisis to a sucessful conclusion. Human nature has a tendancy to cause us to do those things we do best. Therefore we oft-times have to go into the crisis mode before we take action.

Several of my associates were recently involved in Japanese management techniques review team effort. Their findings indicate that the Japanese management system does not want top level managers who operate well in the crisis mode. They pick their managers on their ability to preclude crises. That could be one of the reason why Japanese products are capturing more of the American market.

I will show later that if we find the problems when they

are small they can be corrected with little effort and little expense. It is not patching that we want or need from the system, it is prevention.

If we have 20% of the work force reworking defective products and equal number are busy making the defects. 20% rework, in this case, equates to 40% of the work force and 40% of the labor dollars are spent in making and correcting defects. It should also be pointed out that the cost of finding defects increase rapidly, approximately ten fold, if allowed to procede to the next stage in the line, this is also true of software deficiencies and errors. An error that is found in software documentation costs approximately six (6) dollars an error to detect and correct, whereas at the next level (the first level test) it costs approximately sixty (60) dollars, if the error is allowed to go up to system test, it costs six (6) hundred dollars to find and correct the defect. If the error happens to be a military system that is put in the fleet it could cost six (6) thousand dollars or more to detect and correct, according to the complexity of the system and the level of test at which it was detected. A critical error in a system installed in the fleet such as one used for weapons system deployment or ship protection could cost us an aircraft carrier, a battleship or aircraft that the weapon system was supposed to protect.

Do not be mislead from the preceding example that inspection is the total secret to success. Some companies build layer upon layer of inspection to insure that a nonconforming product, or at least one that they don't know about, doesn't

leave the plant. This is defeating the purpose of the total QA system which is not only to identify and segregate the nonconformances but to preclude them from happening in the first place.

Recently while on a special audit team of a facility, top management and QA personnel prided themselves in the fact that they had an excellent and almost perfect inspection system. During discussions, their QA management more or less implied that nothing got through their inspection process and that the inspection process was the heart of their quality assurance program. They were very adamant in regard to the fact that they were not inspecting and testing quality into the product but that inspection just assured that nothing got through that was nonconforming regardless of the condition of their instructions and procedures. After review of their procedures and operational methods, which were rather poor, it was discovered that hardware, which had been inspected and was ready to go on to the next stage of fabrication, had many soldering and workmanship defects. Because of the workmanship deficiences found by the audit team a complete reinspection of all completed items was ordered and those found deficient reworked. Unfortunately a good many units had been fabricated into the next higher assembly or into the all-up-round configuration. These assemblies had to be disassembled and the problem items reinspected to ascertain that the type of deficiencies found by the audit team were not evident in the outgoing product. Not only was the delivery schedule jeopardized but the disassembly,

reinspection, rework, assembly and retesting activities were very costly.

As I have stated previously, it is an adequate quality assurance program which is cost effective. It is the lack of an adequate program which is the cost driver. I shall provide examples to prove this point. In his book "Quality is Free", Philip B. Crosby states that through the application of an adequate quality system IT&T had measurable, bonified cost savings of 530 million dollars in 1978.

Additional examples which further amplify the ability of adequate QA system to save money and reduce equipment failure rates, can be seem in the figure comparison after take over of American factories by Japanese Management. After take over of the Motorola TV line, Japanese management was able to reduce the warranty repair costs from 22 million dollars to 4 million dollars in less than two (2) years. In addition, the new Quasar TV line more that tripled it's capture of the TV market. I consider this fact to be astounding. Whirlpool Corporation which is now a member of the "Sanyo" family, dropped the retail failure rate of their product from 10% to below 2% in roughly the same time span. The difference between Japanese management and American management philosophies is that instead of talking about Quality the Japanese thoroughly believe in the quality system approach and instills quality thinking into their employees.

Every penny saved in the making of conforming products the first time, and the elimination of expensive rework, makes the company a profit of 1/2 cent. It has been estimated by

Dr.'s Juran and Deming that company's generally spend 10 to 20 percent of their sales dollars on QA/QC and correction of defects, and that with an adequate QA system the cost should be not more than 2.5%. Some examples of the costs associated with the manufacturing of nonconforming products in the DoD procurment environment are now in order.

It should be noted that all the dollar figures have been converted to 1981 dollars.

General Robert Marsh, Commander of the Air Force Systems Command, stated in a speach earlier this year that the hidden plant costs of the contracts administered by the Air Force Contract Management Division was a minimum of 570 Million Dollars. This figure includes only those items directly attributed to scrap, rework and repair at the prime contractors and does not include other costs associated with poor quality systems.

Costs attributed to rework on a low rate production missile buy which only totaled 180 missiles, were estimated by the DCAA to be in excess of 1.15 million dollars. Rework due to workmanship errors attributed to 900 thousand dollars of these costs.

A contract for 40,000 small electronic assemblies which cost approximately 45 hundred dollars each, provided the following figures for a three month production run. One thousand and nine (1,009) defects found, 60% of the fabricated units had to be reworked, 20% of the units had to be scraped. The scrap costs for the three month period was approximately

400 thousand dollars, which projects to a potential scrap cost of 1.6 million dollars for the first years production. The cost of rework was one and one half (1 1/2) time the scrap cost.

Figures recently obtained from the DCAS at a manufacturing facility producing a complex missile system indicated that a defect found at higher level testing cost 12 to 15 thousand dollars to rework and return the unit to the same level of test. Field failures cost the Government an estimated 25 thousand dollars each, not counting the paperwork and handling.

In DoD items, there are other costs assignable to defects which cannot be readily computed. Each time a unit is reworked or repaired the inherent reliability of the system can be easily compromised and the product degraded. In addition, needed weapon systems, undergoing rework/repair, are not available in the fleet which can adversely effect our Military readiness posture.

Several years ago a much needed missile system could not pass OPEVAL testing because of Quality problems inherent in the missile design and manufacture. Upon review of the problems and the processes used to manufacture the missile the investigating team made recommendations to improve the quality of the system. The recommendations were readily implemented by the contractor. Not only did the missile pass the OPEVAL test, the cost to manufacture the missile was reduced by approximately one hundred and sixty percent (160%) and the

missile MTBF increased by a factor of seven point five (7.5).

Before closing, I would like to present one more example of the costs of defects. If, while on a mission, an airplane and pilot are shot down due to a malfunction of the missile being carried for protection we not only lose the cost of the missile and an airplane, but possibly a life as well. With a loss of this magnitude in mind, how can we not want to do it right the first time.

VAPOR PHASE SOLDERING
OF CHIP DEVICES

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ABSTRACT

This paper describes the conception we have of microassembly, from the package up to the board level. New concepts applied in our company to the integrated decoupling capacitor chip-carrier "IDCCC" and to the high thermal conductivity chip carrier "MIA" associated with large size (20 square inches) alumina multilayer substrates allow very high levels of performance to be achieved. Surface mounting of these packages is performed by vapor phase reflow soldering. Fluxless solder bases are presented, as well as the determination of the alloyed areas within the solder microjoints.

VAPOR PHASE SOLDERING OF CHIP DEVICES

INTRODUCTION

We are going to set forth the rationales which led us from the PCB to the hybrid mounted on PCB, and then to the printed circuit on alumina "PCA".

The substrate size is dictated by the "1 function per substrate" concept which makes testing easier and increases reparability. We remark that most of our functions are composed of 60 to 120 packages equivalent to 20 leads. As the selected package is the chip carrier for the following reasons:

* more than 100 leads are possible; as can be seen on table 1, beyond 84 leads, only the chip carrier family can be used;

* reduction in the size of the package and increase in performance as compared to the DIL;

the number of chip carriers defines the substrate dimensions. They correspond to the 1/2 ATR format, that is a substrate size of 6 x 3.4 inches, i.e. 20.4 square inches.

On this substrate, 65 chip carriers equivalent to 20 leads can be mounted, and 130 chip carriers if both sides are used. It should be added that this lay-out density is made possible only through the use of a new chip carrier which has the same size as the others (40 or 50 mils between centerlines) but is provided with its own decoupling capacitor [1]. This chip carrier, named "IDCCC" for Integrated Decoupling Capacitor Chip Carrier allows savings from 15 to 18 % in area.

It can be noted that this substrate size, close to 20 square inches is bound to become very widely used, indeed:

* DOD [2] is substituting a new size (3.79 x 5.30 inches, i.e. 20 square inches) for the SEM format,

* computer manufacturers, more specifically CII and Honeywell, use alumina substrates 4 inches on a side, i.e. 16 square inches,

* consumer products manufacturers such as ITT for color TV digitalization (4 x 6.4 inches),

* for military data processing equipment, Mr DANIELSSON [3] proposes the 6 x 4.3 inch format.

Once the size has been fixed, the material remains to be selected. Many studies are conducted on organic materials, in order to reduce the conventional PCB coefficient of thermal expansion and make it close to 6 ppm.$^{\circ}C^{-1}$.

Table II, below, gives the main characteristics of the various substrates, as well as the price per unit area.

TABLE II - Fig. 2

SUBSTRATE

Material	T.C.E. (ppm/°C)	Thermal conductivity (cal/cm^2/cm/s/°C x 10^2)	COST per dm^2 (Dollar*)
92-94 % alumina	7	4.8	0.15
96 % alumina	6.7	4.3	0.25
Epoxy glass (with copper on both sides)			
. 1.6 mm thick	15	0.034	0.24
. 0.8 mm thick	15 about	0.036	0.22
Epoxy Kevlar (55 %)	6	0.045	0.73
Steel	6	9.3	0.07
Alloy 42	5.3	3.0	0.46
Titanium	7.9	3.4	3.50
Invar/copper/Invar	6.0	3/26.3	0.56
* 1 dollar = 6.5 FF			

As can be seen from this table, alumina is today the best performance-for-money compromise. By construction, this material has the same TCE as the alumina chip carriers. It conducts heat 100 times better than the PCB's, compatible metallizations for this material are well known, and last, its price is almost identical to that of the epoxy glass PCB and much lower than the price of composite substrates based on Kevlar, silica fibers or coated with a complying material (such as EXACTA).

The only argument which could be opposed to this material deals with the maximum size of this substrate. We do not intend to use the same format as the conventional PCB's, since we have shown that an area of 20 square inches is enough to cope with all our needs.

The selection of alumina as substrate material conditions the component mounting process. We do not use vias through the substrate. All the components are suited to surface mounting 4 ; in France we call this "CHIPARDIZATION" which is shorter than "SURFACE MOUNTING".

After a short review of the surface mounted packages, we shall present the work done on multilayer copper-conductor substrate and on vapor phase soldering.

THE CHIP CARRIER CONCEPT

It may seem surprising that this type of package, invented by 3M 15 years ago, did not evolved a lot as compared to the fantastic development experienced by the integrated circuits. This mainly results from the low level

of funding allocating to packaging and connecting processes studies. These last three years, however, the pace of packaging progress has been very high and the chip carriers offer many additional functions.

* 1. Hermiticity function This ceramic package is endowed with the same level of hermeticity as the ceramic DIL or CERDIP in the case of the glass sealed chip carriers. This type of sealing seems much better than the one currently used for the chip carriers and DIL, namely, the soldering of a gold plated cap by means of an AuSn template with 80 % gold by weight. Glass sealing is potentially cheaper and the thermal cycle for closure by use of the HOT CAP SEALER is much less energy-consuming than the methods based on ovens. Texas Instruments [5] has developed this method which is now adopted by other major IC manufacturers.

* 2. Lead number increase This is made possible by the use of lead spacings smaller than 40 mils, either 25 or 20 mils; one TEXAS approach, however, seems to be particularly interesting, this is the OPEN VIA CHIP CARRIER "OVCC" (fig. 3) which uses two staggered rows of leads with a 50-mil centerline spacing which results in an actual combined step of 25 mils [5].

* 3. The integrated decoupling function [1] becomes a mandatory requirement. Future IC's, such as DRAM ans SRAMS, and high speed logic circuit drivers, MPU's, gates arrays, high speed microprocessors, octal drivers, CMOS drivers, etc. will require decoupling techniques in specially designed packages. Various IDCCC configurations have been used for high frequency testing, as shown on figure 4. This integrated decoupling capacitor THOMSON-CSF concept increases the packaging density on substrate, the estimated reliability and significantly reduces the price of the test jigs for LSI and VLSI, because the IC can be tested in the same environment before and after mounting on the board.

* 4. Thermal function Its is ensured by the use of alumina, but with VHSIC (from 2 up to 7 or 8 watts), the use of a ceramic material with high thermal conductivity became mandatory. Beryllia is generally used. At THOMSON-CSF, we decided to avoid beryllia on the following grounds:
   - non availability in Europe,
   - relative cost as compared to that of alumina,
   - chemical toxicity.

   We only improved the thermal conductivity of alumina, without modifying the other characteristics [6]. Thermal conductors, such as copper or tungsten are imbedded in the alumina matrix (see fig. 5). The results indicate that the average thermal conductivity of this METALLIC INSERT ALUMINA "MIA" is more than 4 times that of standard alumina. Figures 3 and 6 show chip carriers implementing the OVCC, IDCCC and MIA concepts.

* 5. Another feature of the chip carriers is the visibility of all the leads, which allows it to be tested after mounting. This also enables modifications by direct wiring from chip carrier to chip carrier or from a chip carrier to the substrate, without resorting to the use of one or two more repair planes in the multilayer substrate. Of course, these operations cannot be performed on the PIN GRID ARRAYS which, furthermore, are a backward step as far as the SURFACE MOUNTING process is concerned.

Substrate design will be much easier, since a large share of electrical and thermal functions will be "borne" by the package instead of by the substrate.

ALUMINA SUBSTRATE

One last point deals with the manufacture of the multilayer substrate and the selection of the conducting material. Many factors have led us to choose the copper-core multilayer [7, 8, 9].

1) The cost of copper, as compared to that of gold. Thus with the 1/2 ATR format, a 5-level multilayered substrate requires 5 g of gold or 3 g of copper whose respective costs are:

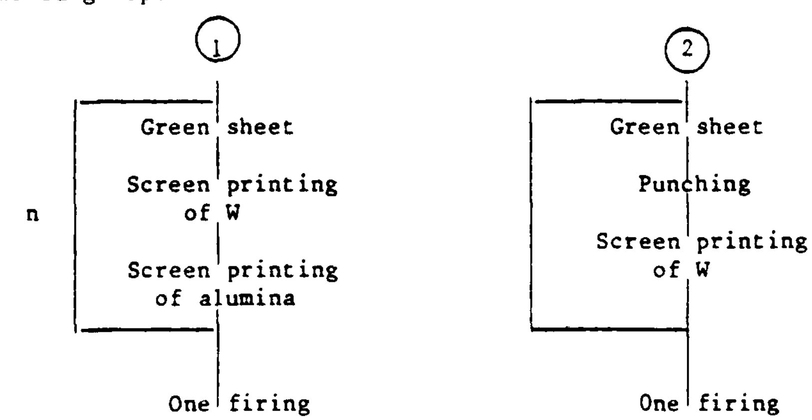
   - 26 x 5 = 130 dollars for gold,
   - 3 x 3 = 9 dollars for copper.

   Consequently, the use of gold cannot be considered for so large formats.

2) Metallurgical compatibility of gold and SnPb alloy is very poor, due to the formation of intermetallic compounds which results in the formation of cracks, as we are going to show.

3) The resistivity of gold is 40 % higher than that of copper.

Nevertheless, it is worth noting that another alumina multilayer technology proves really interesting, namely, co-firing of alumina and tungsten. This technology, which is perfectly mastered by the ceramists can be broken down into two subgroups:



Subgroup 1 includes the same operations as copper or gold multilayer screen printing, but with only 1 firing at 1500 °C in H_2/H_2O atmosphere instead of 25 firings at 900 °C in nitrogen atmosphere. Subgroup 2 also includes only one firing, but the stacking of sheets gives one more freedom degree along Z axis. Indeed, the interference capacity between two signal planes can be reduced by increasing the thickness of the alumina sheet up to 200 or 300 µm, for instance.

Nickel plating of the tungsten leads also provides a good compatibility with SnPb.

We have studied the behavior of the solder joints between multilayer substrates and gold-plated chip carriers made with solders having the following composition Sn 62, Pb 36, Ag 2. Indeed, though the substrates are built with a copper or nickel conductor, the chip carriers are still gold-plated and the capacitors used to be provided with AgPd metallizations, which explains why the silver-saturated soldering alloy has been selected.

All the components have been mounted in vapor phase. Though the vapor phase soldering allows the operations to be conducted at temperatures lower than those required by wave soldering (substrate temperature approx. 200 °C, as compared to 230 or 260 °C in the case of wave soldering), we wanted to check the sensitivity of this process. Consequently, two step durations have been tested (19 seconds and 110 seconds).

SOLDER JOINT ANALYSIS AFTER VAPOR PHASE REFLOW

Bibliographical recall

During the soldering cycle, the Sn Pb alloy cannot reach the thermodynamical equilibrium conditions [10, 11]. We are facing an evolutive system; the mechanical properties of the joints will undergo certain modifications during the aging of the equipment. Otherwise, the presence of elements which constitute the metallizations of the substrate (Cu, Ni) and of the components (Au, Ni, Ag, Pd, ...) leads to the formation of intermetallic compounds [12, 13].

Table III below give the characteristics of the Au/Sn/Pb compounds:

TABLE III

Intermetallic compounds	Formation temperature (°C)	Crystal morphology
Au Sn_4	217	accicularv (white)
Au Sn_2	309	
Au Sn	280	
Au Pb_2	215	dendritic (gray)
Au_2Pb	254	

The studies of P.S. KAY [12] showed that the presence of these compounds affects the properties of the Sn Pb alloys, brittleness, thermal and electrical conductivity, self-diffusion (Kirkendall effect).

In addition to the formation of these compounds, the composition of the solder is modified by the dissolution of the metals which constitute the metallization. Table IV indicates the dissolution speed in Sn Pb of the metals commonly used, at different working temperatures [14].

TABLE IV

Dissolution rate µm/s — Metals	Temperature (°C) 200	215	230
Ni	5.1×10^{-4}	6.3×10^{-4}	1×10^{-3}
Cu	5.1×10^{-2}	7.6×10^{-2}	0.11
Ag	0.56	0.76	1.14
Au	1.27	1.65	2.54

We notice that at 230 °C, the rate of dissolution of gold in Sn Pb is 25 times higher than that of copper; it can reach 2.5 µm per second.

Methodology

The set and measured parameters are presented in table V.

TABLE V

Set parameters		Measured parameters
. Vapor phase reflow time (215 °C): - 19 s - 110 s	- Substrate 96 % Al_2O_3	. Optical inspection of the joints
. Thermal cycles (- 55 °C to + 125 °C): - 0 - 500 - 1000	- Substrate metallization from DN Cu	. X-ray mapping on cross-section: - near chip carrier - near the substrate
. Storage at 125 °C: - 0 h - 500 h - 766 h	- Gold metallization of chip carrier "3 M"	. X-ray profile on metallographic cross-section: - near chip carrier - near the substrate
	- Solder composition: Sn 62 % by weight Pb 36 % by weight Ag 2 % by weight	
	- Flux: LONCO 7525 TA	
	- Pre-heating: 180 °C	
	- Solder bath temperature: 230 °C	
	- Dipping time: 5 s	

Analysis

- Preparation of the samples:

  The chip carriers (40 leads) and the substrates have been tinned at 230 °C for 5 seconds. Each element (chip carrier and substrate) as well as the assembly has been weighted before and after tinning.

Thus, an estimation has been made, on the one hand of the weight of each microsolder, and on the other hand of the tin process uniformity.

Table VI shows the results obtained. It is noteworthy that the quantity of solder in the assembly is relatively constant (± 13.5 %). This fact permits us to ensure the reproductibility of the various elements concentrations (Au, Pt, Sn, Pb, Ag) in the samples.

TABLE VI

Components	Weight of each microsolder Mean value (mg)	Standard deviation (mg)	Accuracy at 2σ (%)
Substrate	0.263	0.05	± 38
Chip carrier	0.407	0.034	± 16.7
Assembly	0.669	0.045	± 13.5

These measurements have been made on 1240 solder joints. It is interesting to note that the sum of solder weight on the chip carrier and on the substrate is well correlated with the weight of solder for the assembly.

During aging and cycling tests, samples where taken and analyzed, metallographic examinations were performed on cross-sections. All analyses on metallographic cross-sections where carried out near the following interfaces (fig. 7):
. solder joint/Au Pt metallization (area 1),
. solder joint/chip carrier (area 2).

- Analaysis method

Scanning Electron Microscopy (SEM) and Energy Dispersive Analysis of X-rays (EDAX) were used with a CAMEBAX system.

Metallic elements of the solder/metallization couple were mapped, and the concentration profiles were recorded.

Results

EDAX was used to choose the characteristic X-ray of each element and to follow the evolution of their concentrations.

The main metals used in the metallizations are the following: Sn, Pb, Ag, Au, Pt, W, Ni.

Looking at these diagrams and at the spectrum analysis, one can be confused by Au and W:

- Au, $L\alpha$ = 1.276 with LIF = 0.317
- W, $L\beta$ = 1.281 with LIF = 0.318.

Consequently, we excluded the L rays and chose the Mα rays with a crystal TAP, thus eliminating any ambiguities. Let us now analyze the influence of the various parameters listed in table V.

- Influence of vapor phase reflow time

No difference is noted with Sn and PB, whereas diffusion of Au into Sn Pb is slightly better after 110 seconds (figure 8) than after 19 seconds (figure 9). This is normal, for diffusion coefficients are much higher in liquid phase than in solid phase. An extended alloyed area, however, exists after 19 seconds as well as after 110 seconds. This area is formed during the first seconds, and it is no use extending the gold diffusion time. The 19 second reflow time has been retained for subsequent testing.

- Influence of thermal cycling

The cross-section at time t_0 (fig. 10) and after 1000 cycles (fig. 11) shows a crack and an area with a different aspect between the chip carrier and the crack. If we combine the Sn and Pb X-ray mapping at t_0 (fig. 12 and 13) with those after 1000 cycles (fig. 14 and 15), we can note a very important segregation between Sn and Pb. This probably results from the decrease of Sn solubility into Pbα during the temperature cycle (- 55 °C to + 125 °C).

The gold X-ray mapping after 1000 cycles exhibits an extension of the gold-rich area. If Sn, Pb and Au concentrations are superimposed, it can be noted that gold-rich and tin-rich areas overlap. Ni and Ag concentrations do not vary significantly.

- Influence of storage at 125 °C

After storage for 766 h at 125 °C, the tin, lead and gold X-ray mapping (fig. 16, 17 and 18, respectively) exhibit three separate areas:

- lead-rich layer (area E) (fig. 16 and 17),
- Au_n Sn_m alloy area (fig. 16 and 18) of mean thickness 12 µm,
- an area C where Sn (fig. 16) and Pb (fig. 17) are depleted.

Knowing that there is a layer of nickel under gold, the evolution of nickel concentration has been checked in all the subsequent analyses (fig. 19). The evolution was not very extensive, except after storage for 766 h at 125 °C.

In fact, a high concentration of the element can be seen at the upper limit of area C on the Ni X-ray mapping (fig. 19). The diffusion of Ni from the surface of the chip carrier to the limit of C inhibits the formation of the Au_n Sn_m compounds. It is known that Ni diffuses very quickly in gold; this effect is particulary common in thin film technology (Ni Cr + Au).

- Discussion

The long aging period exacerbates the formation of intermetallic compounds. This fact allows us the confirm that the zones under observation during a thermal cycle, though less developed, are the same

same type. We have noticed cracks between 500 and 1000 cycles and we wanted to determine the concentration profile of Au, Sn and Pb near them (fig. 20).

X-ray profiles have been established on these three elements (fig. 21) and we observe that:

. the crack is at the interface between Au_n Sn_m and Pb,
. Sn and Pb peaks clearly show the segregation between these elements after aging,
. all peaks strictly correspond to segregations, as we can see on the Au X-ray mapping of the analysis area (fig. 22).

All these analyses after cycling revealed that the deterioration causes have to be looked for in the solder joint itself. This fact must be added to the mechanical phenomenon due the mismatch of substrate and chip carrier linear expansion coefficients, as previously demonstrated [15] The development of microcracks takes place at the interface of the Sn Pb alloy areas and Pb. Consequently, dispensing with gold will avoid the existence of these areas.

We have to note that it is not realistic to measure the failure rate of the microcracks using conventional optical or electrical systems. We have seen the microcracks grow inside the solder. A non-destructive method, acoustic microscopy, which is still in the experimental phase of development, will probably enable their detection. However, a new investigation and check method mentioned by Mr. J.D. Raby [16] and based on the thermal signatures of joints after heating by laser [17] seems extremely interesting and is certainly a very specific evolution in the field of microsolder joints inspection.

Finally, after all this testing, we conclude that gold should be dispensed with in the chip carrier as well as in the substrate. The use of gold for the substrate is a goal which has already been achieved at CIMSA, since copper or nickel is used instead. Removal of gold from the chip carrier is achieved by dipping it in a bath of Sn Pb at 230 °C ± 5 °C for different periods of time: 0.5, 30, 60 and 300 seconds.

Levelling was used to mechanically remove the gold-rich solder. The Au X-ray mapping made after 0.5 s shows that gold has been completely dissolved. These results have led us to add this operation in our fabrication line.

SURFACE MOUNTING OF COMPONENTS

Different mounting techniques using several methods of heat transfer are used:

- convection (in reflow furnace),
- conduction (belt reflow soldering system or dipping in solder bath, laser),
- condensation (vapor phase reflow).

On the basis of the results we obtained from the analyses performed on microsolders and mounting of tin-lead, the following criteria have been settled and must be complied with.

1) Temperature uniformity, regardless of the size of the components.
2) Reflow temperature lower than the formation temperature for the intermetallic compounds.
3) Flux activity must be as low as possible and it must be easy to clean. Avoid oxidation and decomposition of this flux. Flux oxidation begins at 170 °C and around 290 °C carbon deposits become important. The process should allow flux-free soldering in a further time.
4) The process must be such as allowing soldering on both sides of the substrate.

So far now, none of the existing reflow processes met these 4 criteria.

The classical reflow furnace, which necessitated very high temperature peaks to supply enough energy to the components with high thermal mass, did not satisfy the criteria.

Dipping in solder bath at about 230 °C or in a wave at 260 °C satisfies criterion 1, but it does not meet the other three.

Belt reflow soldering does not respect criterion 1 because the thermal resistances are not predictable, and compliance with criterion 4 is impossible.

Vapor phase reflow meets all these criteria. With this process, the potential energy (latent heat of condensation) is stored in the vapor and released during the phase transition to liquid during condensation. A schematic view of the basic condensation soldering system is shown in figure 23.

We have been using this technique for 5 years, first with a HTC 14-16 machine, and then with a French PIEZOCERAM VPR 30-40 machine which ensures very good reproductibility.

<u>Results</u>

A four copper conductor layers on alumina substrate with chip carriers (from 16 to 64 contacts) are used. The temperature is measured at three levels (fig. 24).

- Level 1: holes (dia 0.6 mm) have been made inside the alumina substrate, so as to insert a thermocouple to measure the bulk temperature.

- Level 2: a flat thermocouple, thermally bound on the substrate allowed the surface temperature to be recorded.

- Level 3: the temperature inside the chip carrier, measured classically with a diode (1N 914) enables the monitoring of the temperature profile during the cycle.

Typical thermal responses at these levels are shown on fig. 25. We can see that:

- the temperatures inside the substrate and on its surface are close to each other (197 °C and 204 °C),
- the temperature in the silicon diode is as low as 165 °C.

The selection of the setting points has been done to minimize the temperature-time couple. Surface temperature profiles are presented on the curves (fig. 25).

If we want to reduce the total cycle, we have to increase the down speed, but the up speed will be limited by the "effect of Oar". The primary liquid vapors are drawn up by the assembly.

In addition, during the upward phase, a step should be performed at approximately 100 °C, so that the vapor pressure of the primary liquid condensed by the substrate be high enough to remove this liquid film and avoid loss of product.

A this cooling level, the VPR 30-40 machine uses a secondary liquid (freon) spray. The bonusses of this system are many. One the one hand, this spray breaks down the primary liquid film, on the other hand the secondary liquid is vaporized at the contact with the substrate and secondary vapor phase, thus it never touches the primary liquid, whose temperature is 215 °C with FLUORINERT FC 70 or 240 °C with GALDEN LS, which decomposes it and produces HCl.

This observation and the shapes of the curves are typical of the thermal capacity charge. The behavior of the thermal response is typical of a newtonian heat flow and is governed by the following formula:

$$\ln \frac{T - T_\infty}{T_0 - T} = \frac{hS}{\rho CV} t$$

with:
- C specific heat of the body
- ρ density of the body
- h average surface conductance
- S surface area
- T temperature
- T_∞ temperature of the fluid
- T_0 initial temperature

The heat transfer ratios were obtained from a semi-log plot of the data, fig. 27. Such a plot indicates that the thermal response is exponential and, hence, the slope is proportional to the heat transfer coefficient. The plots No v1, v2, and v3 showed two separate linear segments, indicating two separate time domains with exponential temperature rise. We can see that the change in slope always takes place at the same temperature (48 °C), the boiling point of trifluorotrichloroethane (freon). Curve v4 consists of three segments with different slopes, but with a heating power higher than for curves v1, v2 and v3. Curve v5 was obtained with the same test specimen, but without the holder. Only the substrate thermal capacity is to be considered.

Downward and upward speeds are almost instantaneous. The substrate has been dipped directly into the primary vapor phase. It can be seen that the

thermal charge of the holder, when parallel to the substrate, does not affect the slope of v5, and v1, v2, v3 are very close. This reflow process has been applied to different assemblies:

- five-level gold multilayer (2.3 x 1.6") with 20 chip carriers,
- copper multilayers (1/2 ATR 6 x 3.4") with 60 chip carriers (fig. 29)
- thermal print head (10 x 2") with 36 chip carriers with 40 mils pads.

Every substrate has 1152 solder joints. The defect rate after reflow was less than 1/2000.

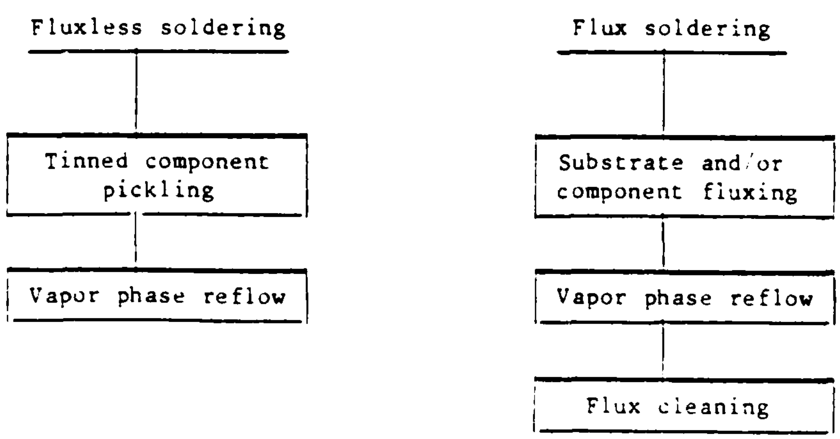
The reflow cycle currently implemented for this product is presented on fig. 28. The reflow cycle time, i.e. 63 seconds, has been determined on the basis of three parameters:

- downward speed is the same as upward spped,
- upward speed cannot be too high, in order to avoid vapor loss,
- reflow time must be sufficient to ensure good wetting.

CONCLUSION

It is pretty well known that "chipardization", and more specifically with the chip carriers, presents a flux cleaning problem. Indeed, it is really difficult to ensure that all the flux have been removed from beneath the chip carriers. This is the reason why we are still conducting studies on fluxless soldering. As a matter of fact, vapor phase allows the soldering operation to be carried in neutral (non oxidating) atmosphere, which is almost impossible with wave soldering.

This atmosphere, however, is not usually reducing, though hydrochloric acid produced by the decomposition of freon may facilitate Sn Pb deoxidation. Consequently, hydrochloric pickling must be added before reflow. This seemingly additional operation actually dispenses with two others.



Finally, the replacement of one or more chip carrier(s) must also be performed without flux. Removal is performed by gas-gun; fluxless mounting of

another package still presents problems. A new mounting method with localized vapor phase might be possible, as suggested by James Howser [18].

At last, further to the mounting-related problems, we have tried to stress the importance of the packaging, which of course is intricately linked to that of the substrate.

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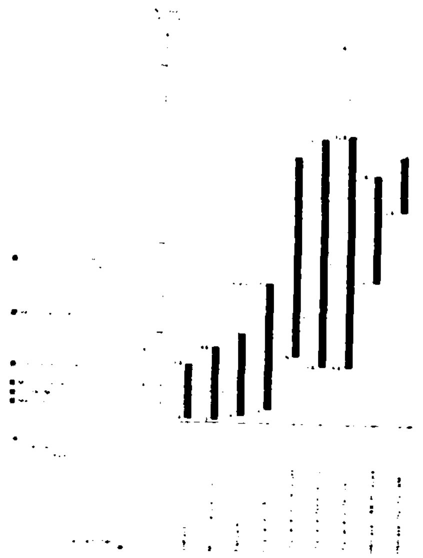
TABLEAU

RELATION ENTRE LES TYPES DE CIRCUITS INTEGRES ET DE MICROBOITIERS



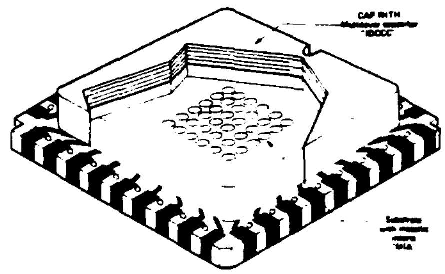


FIG. 3 - DRAFT OF THE O.V.C.C. WITH «MIC» AND «IDCCC» CONCEPTS

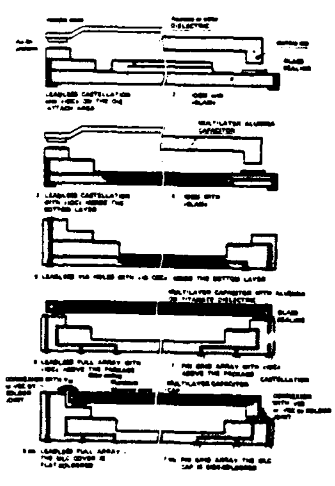
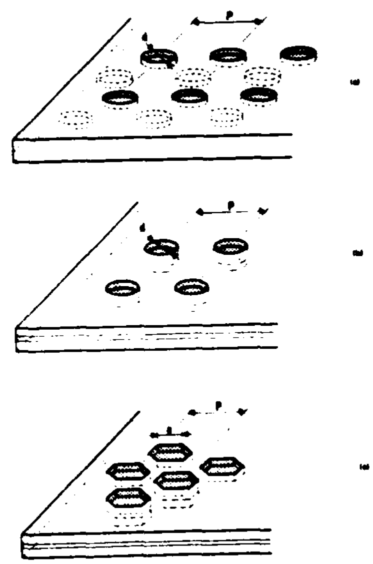
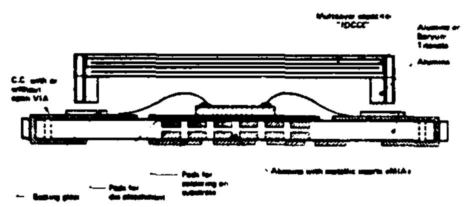


FIG. 4 - CERAMIC PACKAGE WITH INTEGRATED DECOUPLING CAPACITANCE



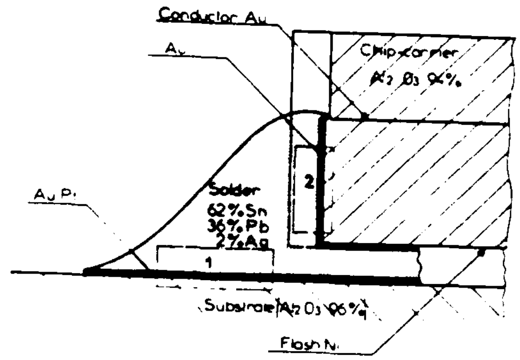
CONFIGURATION OF ALUMINA SUBSTRATE WITH ROUND METALLIC INSERT SHIFTED (a) FACING (b) OR WITH HONEYCOMB FACING (c)

FIG. 5



CUTAWAY OF A SLAM WITH MIC AND INTEGRATED DECOUPLING CAPACITOR

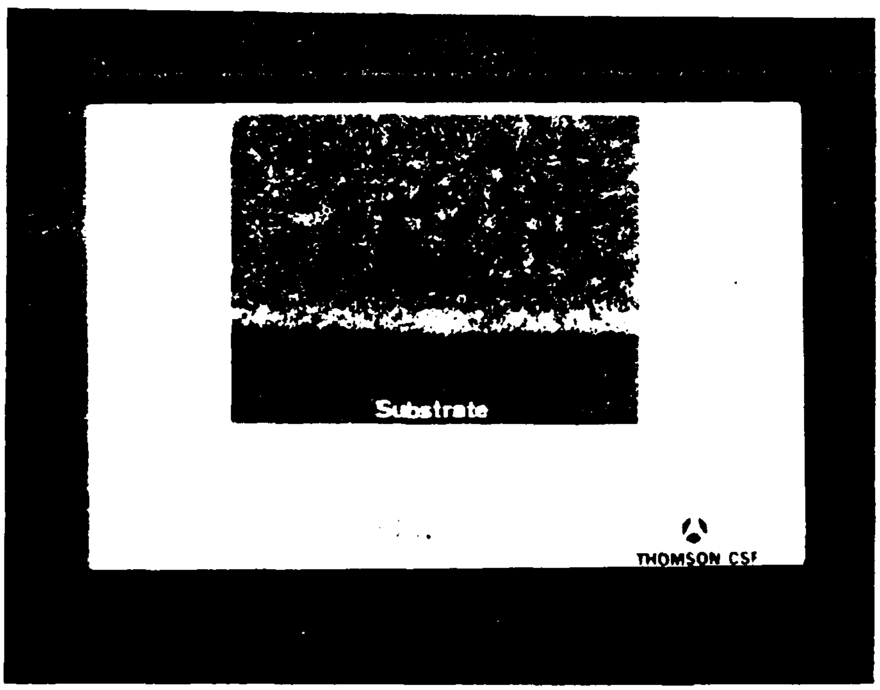
FIG. 6

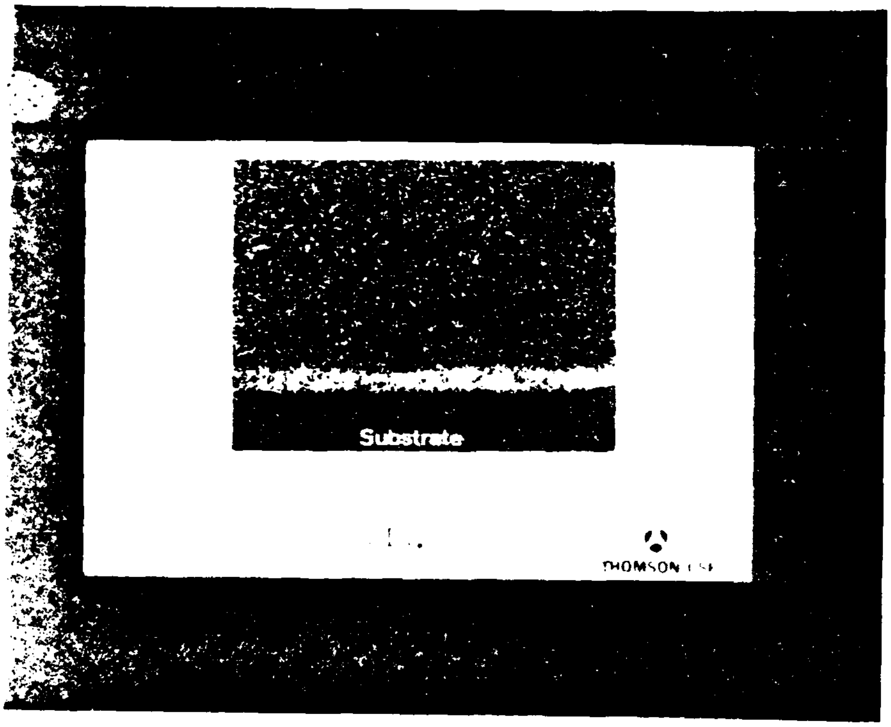


1 — Analysis area substrate

2 — Analysis area chip.carrier

THOMSON-CSF





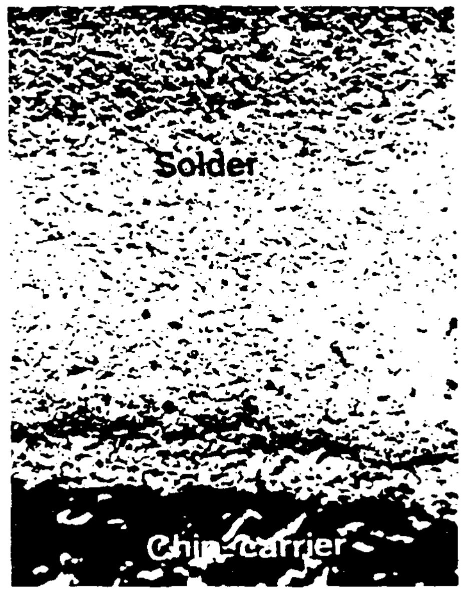
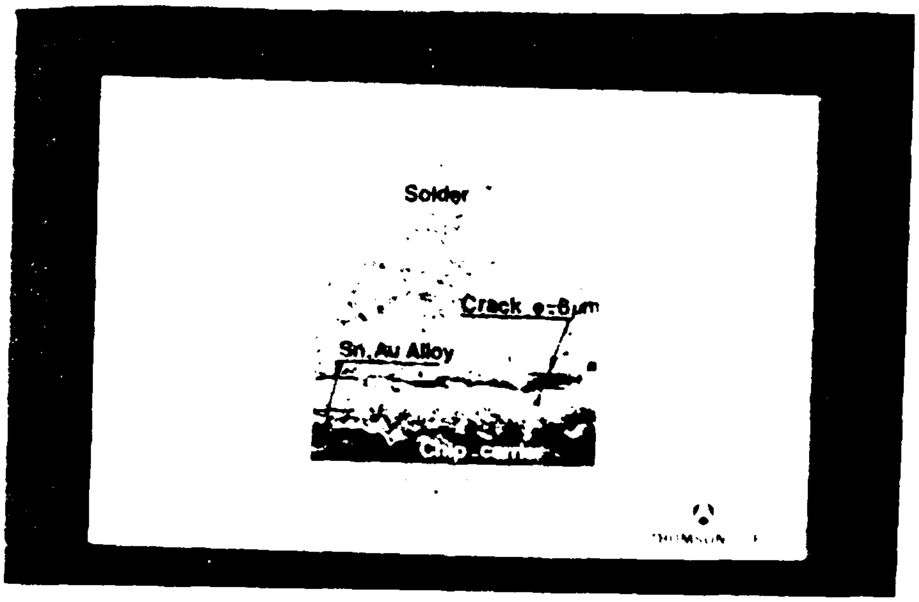


FIG. 10

Metallographic cross-section before ageing (reflow time 19s ;chip-carrier)



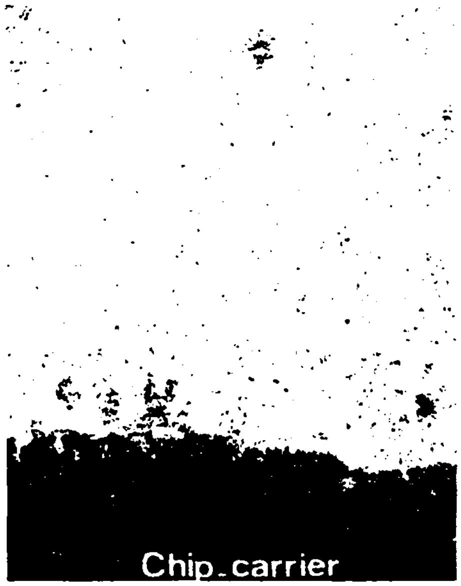


FIG. 12

Sn, X-ray mapping before ageing
(reflow time 19 s ; chip-carrier)

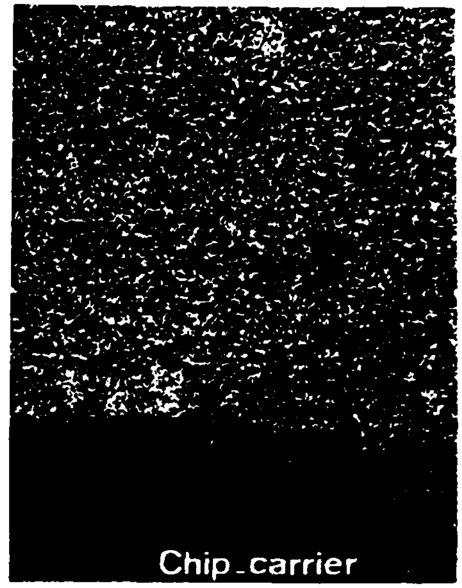


FIG. 13.

Pb, X-ray mapping before ageing
(reflow time 19 s ; chip-carrier)

FIGURE 14

Sn, X-Ray mapping after 1000 cycles
(reflow time 19 s ; chip-carrier)

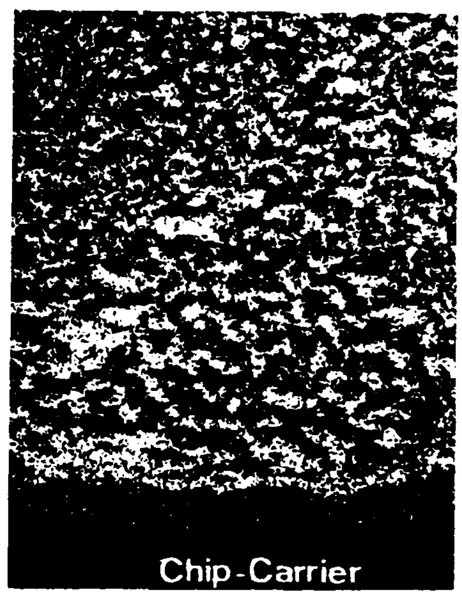


FIGURE 15

Pb, X-ray mapping after 1000 cycles
(reflow time 19 s ; chip-carrier)

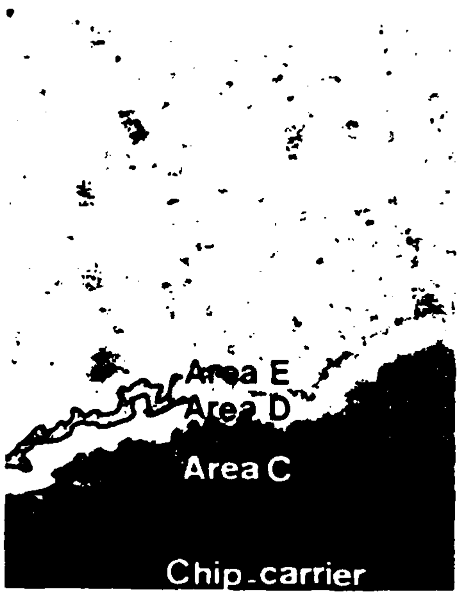


FIGURE 16

Sn, X-ray mapping after storage 766 h at 125°C (chip-carrier)

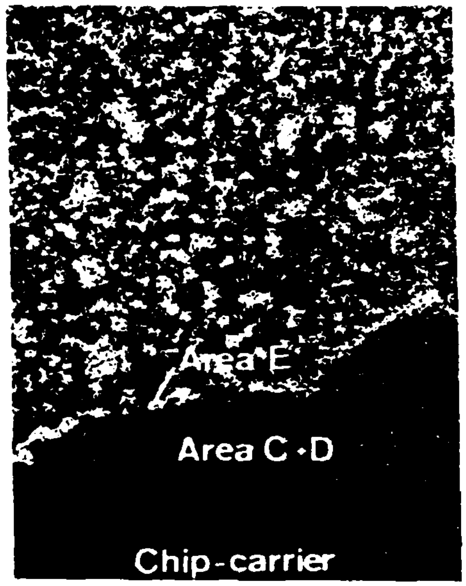


FIGURE 17

Pb, X-ray mapping after storage 766 h at 125°C (chip-carrier)

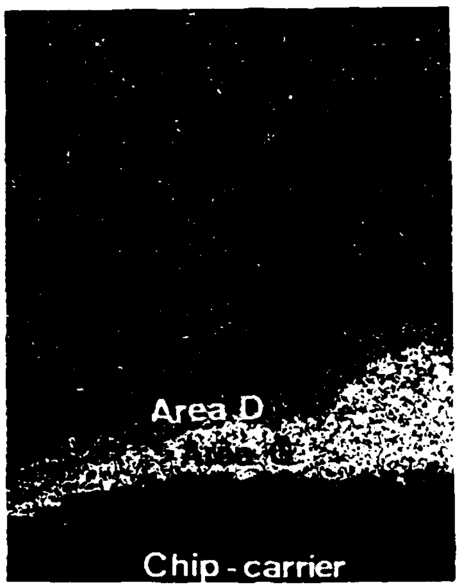


FIGURE 18

Au, X-ray mapping after storage 766 h at 125°C (chip-carrier)

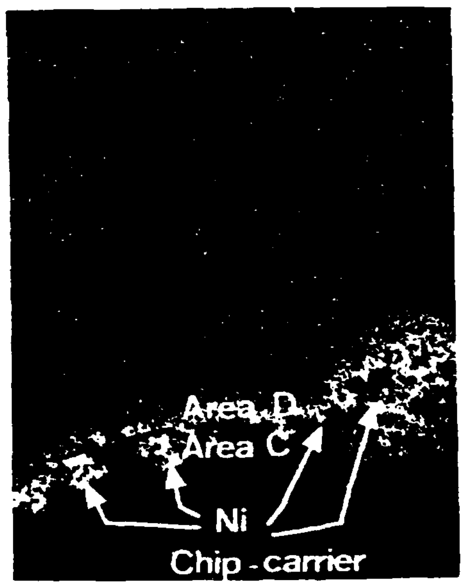


FIGURE 19

Ni, X-ray mapping after storage 766 h at 125°C (chip-carrier)

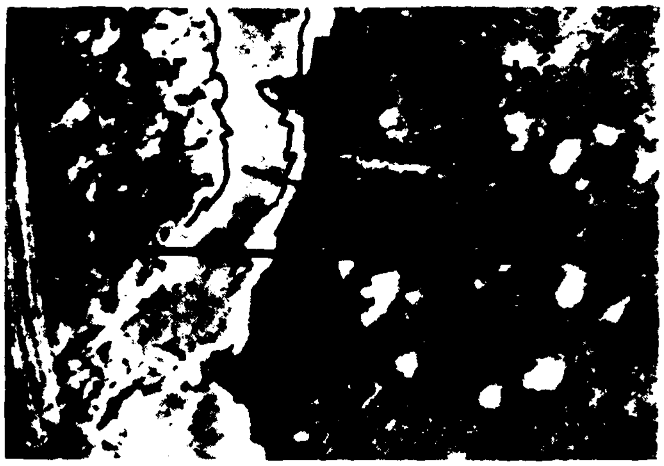
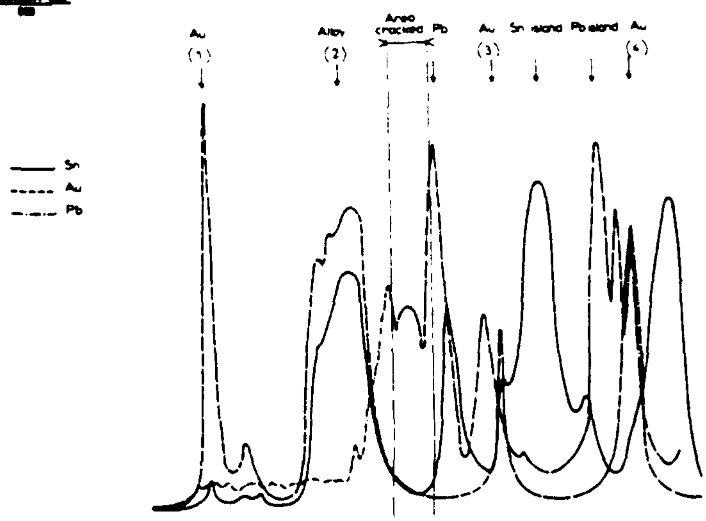


FIGURE 20

Metallographic cross-section through a crack.

X RAY PROFILE Fg. 21



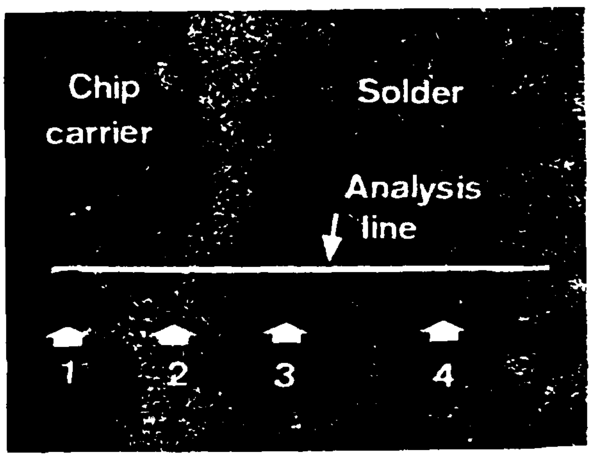


FIGURE 22

Au, λ-ray mapping after 1000 h at 125°C.

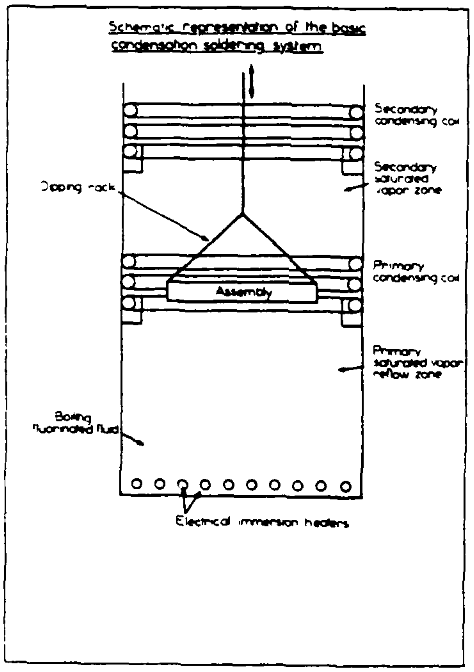
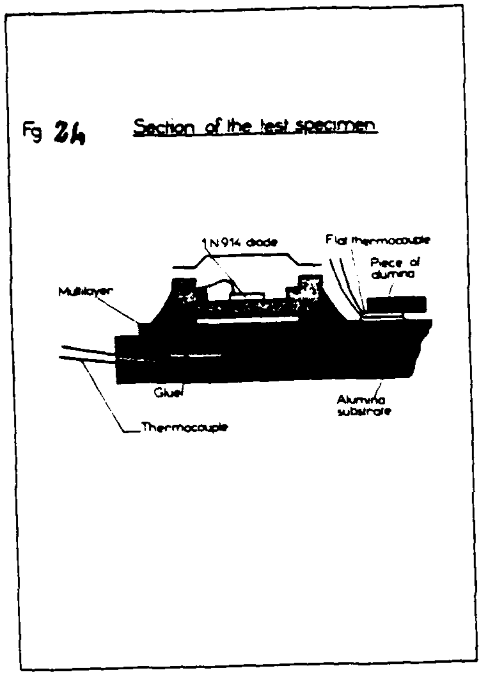


FIG. 23



Fg 24 Section of the test specimen

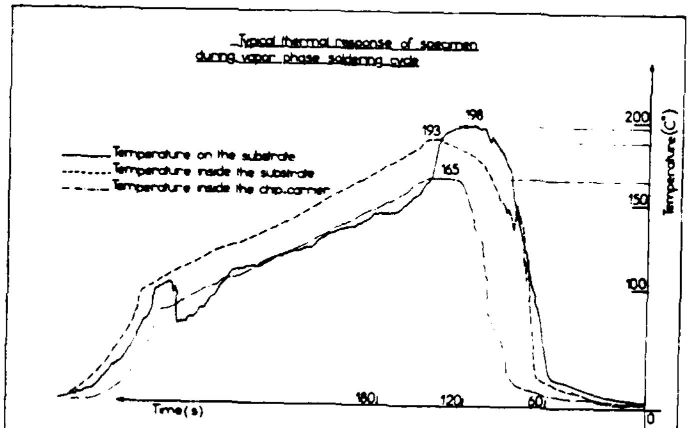


FIG. 25

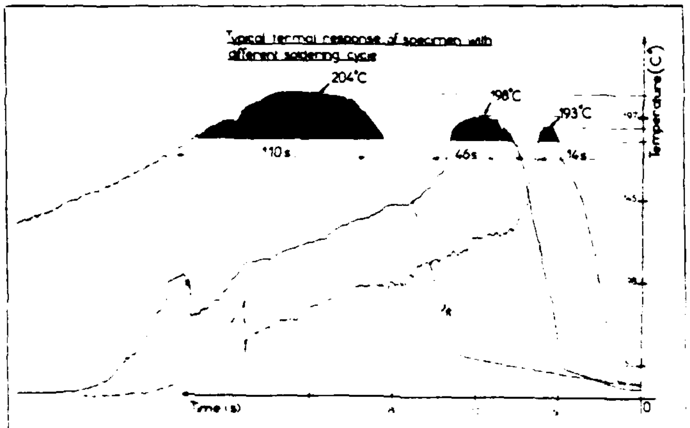


Fig. 26

Fig. 27 - Temperature Vs time

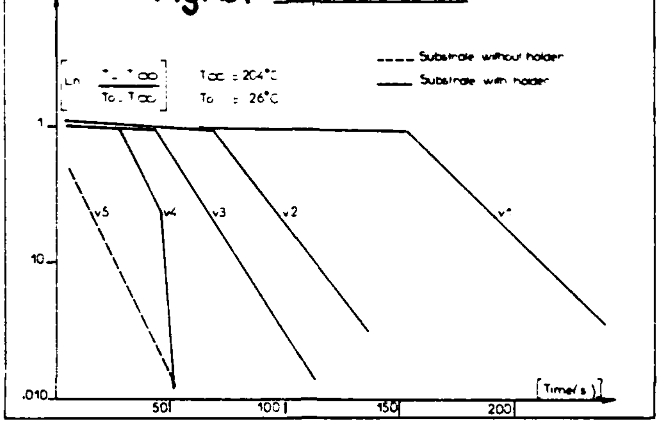
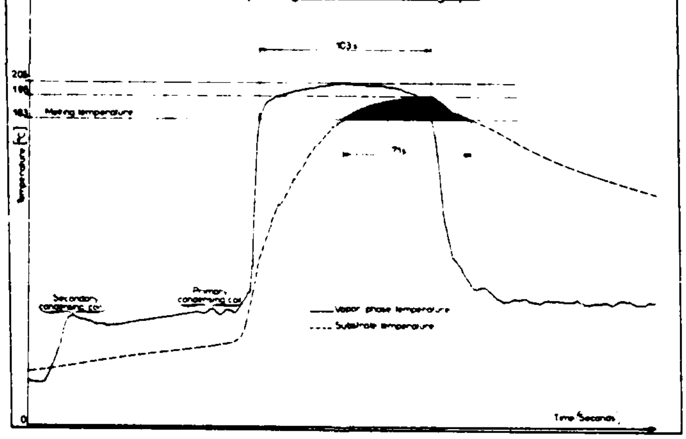


Fig. 28 Typical thermal response of large multilayer assembly during condensation soldering cycle



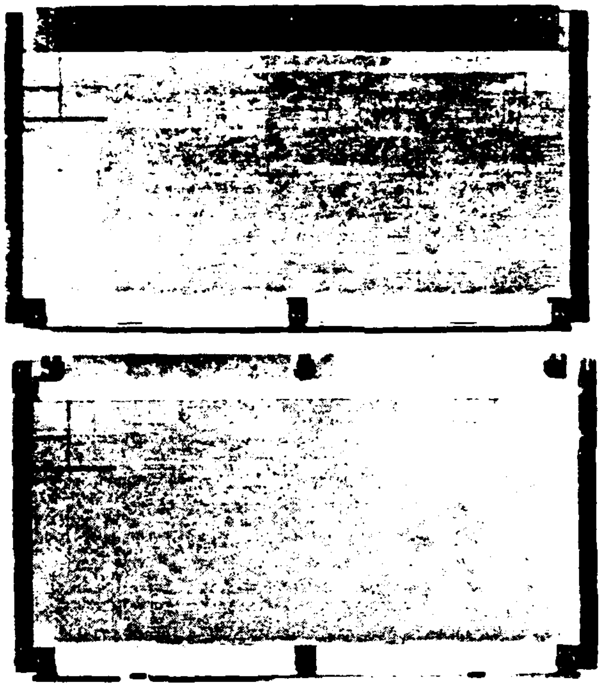


FIGURE 29

FIVE LEVELS COPPER MULTILAYER ON ALUMINA SUBSTRATE (6 x 3.4 INCHES) - RECTO AND VERSO

Paper given at the 7th Annual Soldering Technology Seminar Naval Weapons Center,China Lake, Cal. 27 February 1983

CREEP AND FATIGUE TESTING OF MICRO SOLDER JOINTS

Gert Becker, Telefonaktiebolaget LM Ericsson, Stockholm, Sweden

INTRODUCTION

Today it is common knowledge that solder joints can be subjected to such stresses that they crack due to fatigue. This problem is not too many years old. It appeared with the introduction of plated through holes,became a serious problem with the use of conformal coatings and is still with us as we introduce the chip carrier and other surface mounting techniques.

THE CAUSE OF THE PROBLEM

The problem simply lies in the fact that heat is generated in the electronic components, fig 1, which makes them expand. This heat is dissipated through radiation and convection. The heat which is dissipated through convection flows through the solder joint to the board, heating up both the solder joint and the board. The board material has a different coeficient of expansion to the chip component, the chip carrier. This thermal mismatch, and the delay in the heating of the chip carrier and that of the board, cause a relative movement between the chip and the board. As both parts are rigid in comparision with the solder joint,the repeated movement

cause repeated stress in the solder joint which in due time lead to a fatigue crack.

A very important point which must be taken into account is the temperature reached in the component during use. Depending of the type of component and the power generated in the component, temperatures between 90°C and 160°C may be obtained. This gives us a steady state temperature in the solder joint of let us say 60°C to 110°C. Thus a solder must be choosen which gives us the desired strength properties at those temperatures. We know that the strength of solder decreases with increased temperature,fig 2, and that ternary impurity eutectics in the solder melt at lower temperatures than the solder itself. Regarding the strength properties there seem to be a limit to which a solder joint can be heated . According to Hieber (1) there are two different levels of activation energies for solder joints which meet at 114°C. An analysis of Späth (2) shows a change in the creep properties of solder between 120 ° C to 150 ° C. On the other hand an upper limit is sat with the soldering temperature when soldering surface mounted components in massproduction. If for instance the condensation soldering method is used a melting temperature for the solder less than 215°C is required. These two temperature limits largely restrict the choice of solders with suitable properties for the task to 60/40 tin/lead solders.

TO PREDICT THE LIFETIME

It has become quite common to use the MIL-STD 202F Method107D with temperature cycling between -55°C and + 125°C with half an hour at each temperature to test solder joints for their fatigue life. This test was originally designed to test components and the printed wiring boards. The method seemed to be applicable to test solder joints as well. But on examining the literature you will soon find many different values obtained for the number of cycles to fracture, ranging from some ten cycles to more than a thousand cycles .

Apparently some ten cycles are not sufficient and whether some hundred or more than thousand cycles are sufficient or not is nowhere clearly stated. So the question is what number of cycles to failure is acceptable for a specific design.

The solution of this problem seems to lie in the experience that the number of cycles to fracture is proportional to strain. This can simply be shown graphically, fig 2. In this diagram the x-axis represents the number of cycles to fracture and the y-axis the strain, which in our case shall be represented by the temperature difference ΔT which causes the strain. The number of cycles to fracture found by the MIL-STD test (-55°C to +125°C, ΔT = 180° C) is in this diagram represented by one point.

Now Miners rule says,that at failure the sum of the ratios of the actual number of cycles at each strain to fracture to the number of cycles to fracture at that strain is one (fig 3). Miners rule is then used to translate the number of cycles to fracture obtained gained by the MIL-STD method to the number of cycles at other strain levels.

Miners rule is valid for fatigue testing.The problem we have to deal with however has a strong component of creep in it. For steels methods have been developed which are based on the idea of the used life and take into account both fatigue and creep (3). Such methods are not available yet for solder due to lack of materials data for solder.

CRITICISM OF THE PREDICTION OF LIFETIME

In fig 2 a curve was given which represented the relation between the strain and the number of cycles to fracture.Unfortunately there are not sufficient experimental data available to confirm that the curve used for calculation must follow curve 1.

Creep tests have shown (1) that even small changes in the composition of solder give large changes in the lifetime.If this is valid for fatigue tests too the lifetime can be reduced from an expected 40 years to 20 years, curve 2 in fig 2. We know too that a solder joint changes metallurgical with time due to diffusion. Changes in pull strength have been measured (5). Therefore it is not unlikely that a real fatigue curve could look like curve 3 in fig 4, which suggests a sudden drop in lifetime.If this happens, it would have serious consequences.

Other factors which has carefully to be taken into account when predicting the lifetime from values given in literature are first the spread of the results,fig 4, and secondly what precisely the given value indicates,whether it is the mean value, the value for survival of 90 % of the samples or what? This is important, as minor changes are of great influence on a logarithmical scale which is used in such diagrams are of great influence. In the case shown here a wrong assumption could reduce the lifetime from 40 years to less than 20 years.

Miners rule said that the sum to fracture of the ratios of the number of cycles at each strain to fracture to the number of cycles to fracture at that given strain is one. It has been shown,that the sum can vary between 0.5 and 2.0 (6) or even more (7). Values below one are obtained if the sample is subjected first to a high strain and then to small ones. If the sample is first subjected to low strains and then to high ones, values greater than one are obtained.Solder joints are in general subjected first to high strains during their lifetime. That there should be a difference in the value is quite obvious. We know for instance that materials can be given higher strength by working. So do solder joints.

The relations which have been shown graphically can also be formulated mathematically. Coffin and Manson have found the rule for the fatigue life that the number of cycles to fracture is proportional

to strain,fig 5. Taylor,Brierley and Pedder (8) have developed this equation for the use of chip carriers,fig 5. This equation tells us that the number of cycles to fracture depends on material properties as e.g the Poisson ratio v, the contraction e and the power factor as well as on design parameters such as the height h of the solder joint for a surface mounted component.

In the literature values for the Poisson ratio values of 1 - 5 can be found and for the reduction factor e 0.5 - 1.5. Depending on what values are used,the lifetime can at most vary by a factor of about 25. The spread given with this factor is too large to be acceptable for a forecast of the lifetime of the solder joint.

We meet further problems. The modulus of elasticity is changed to much lower values if the temperature of the metal increases. And for solder above room temperature no modulus of elasticity can be established. As the modulus of elasticity is one of the determant factors in the strength of materials,this has the consequence that no extrapolations to higher temperature behaviour can be drawn from fatigue tests at low temperatures. This is important to know - for fatigue at higher frequencies - in the range of resonancefrequencies - can be quite different in character.

More arguments could be put forward as a warning not to use general laws uncritically. We can learn two things from this discussion. The first is that we have carefully to analyse the working conditions for our solder joints. And the second is that we do not have sufficient knowledge about the mechanical properties of solder or solder joints.

ANALYSIS OF THE WORKING CONDITIONS OF THE SOLDER JOINT

From what has already been said it has become obvious that we face another problem. When designing a solder joint very little is known in general about what stresses the solder joint will be subjected to. This knowledge however is a precondition for forecasting the lifetime of the solder joint. In fig 6 such an analysis is shown. We see that the greatest stress is induced at the beginning of the life of the board, during production. The number of the cycles is low however. At the other end the number of estimated cycles is large, 350 000,
but the stress is estimated to be low, ΔT being 40°C. And it is this large number of cycles which makes the effort of determining the fatigue properties necessary, for they determine the lifetime of the equipment.

This analysis reveals too that we have to face different types of strength problems with our solder joints. Obviously we are not dealing only with simple fatigue problems as shown in fig 7, left figure. We see that we have a strong time determined component in the fatigue of the solder joints. It may be so great that the relaxation and creep properties dominate, fig 7 right figures.

STRENGTH OF SOLDER JOINTS

The analysis of the working conditions of solder joints in the equipment has shown that the fatigue, the relaxation and the creep properties all determine the lifetime of the solder joint.

It is known that it is not possible to draw conclusions about creep from pure strength tests to creep (4).

Koch and Wasserbäch (5) have shown, fig 8, that there is a relation between the creep strength, the fatigue strength (Zero minimum

stress) and the fatigue strength (Zero mean stress) in that the zero mean stress gives the longest time to failure compared to the zero minimum stress and creep strength,which gives the shortest time.This gives a certain amount of help in estimating the lifetime due to different types of stress. It has to be observed that the influence of different testing frequencies has not been taken into account here.

TESTING THE STRENGTH OF SOLDER JOINTS

When discussing the problem of the strength of solder joints in equipment you come to a point where a decision has to be made in order to convince yourself about the reliability of the design. It is necessary to carry out a test, such as the cycling between -55°C to + 125°C.But it is costly to select suitable solders ,and to investigate the properties of the solder and the joint by this method.

Therefore it is necessary to choose a simple sample and test method which allows comparing of different solders, and different manufacturing and ageing conditions in the different strength tests. Such a sample is the ring pin sample according to ISO/DIS 3683, fig 9 which has been miniaturized by the Siemens Corporation.This small sample is now used by Ericsson as well.The testing conditions are described in (4).

RELAXATION OF SOLDER JOINTS

Solder joints tend to relax. Relaxation is the decrease in the load with time. The relaxation properties of different solder compositions have been investigated with the ring pin method at different loads and temperatures.The results are given in fig 10.

Data obtained during the relaxation test are firstly the time from the moment the load was applied to the sample until the relaxation starts and secondly until the relaxation has ended as well as the residual load after relaxation.

It was found that both the time for the beginning and the end of relaxation decreased with increased temperature. Even the load level to which the material relaxed decreased with increased temperature.

This behaviour was found also to be valid for the case where relaxation started at different load levels. In most cases the load level after relaxation was higher for a low load level then for a high load level. The movement between the ring and the pin after relaxation increased with increased load level,but decreased with increased temperature.

An answer was found to the important question of whether minor amounts of impurities could alter the relaxation behaviour of 60/40 tin lead solder. Zinc showed a clear tendency to improve the relaxation behaviour bot at higher load levels and at high temperatures. Silver gave at all temperatures and load levels a remarkable improvement in the relaxation properties. This means that the relaxation started later and ended later than for 60/40 solderr,as well as a higher load level being maintained after relaxation.

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The good strength properties of silver are known. But that zinc,in general considered to be deleterious can give a positive effect is new. This result shows that there are possibilities for material development which may lead to improved creep and fatigue properties.

CREEP OF SOLDER JOINTS

The solder which was tested on relaxation was tested in creep too. The data obtained from creep test is the lifetime for the sample. The lifetime is defined as the time at which the pin has moved 0.5 mm by creep relative to the pin.

Fig 10 shows the values obtained for both types of testing. We see that the materials tested have the same ranking both for the creep and relaxation tests. This is understandable as a sample in the creep test - which works with constant load - will relax at higher loads in the beginning before it continues to creep. As creep tests are time consuming they can be replaced with success with a relaxation test for the evaluation of different materials.In fact relaxation tests are more useful for judging the behaviour of equipment and for planning different types of fatigue tests.

FATIGUE OF SOLDER JOINTS

A solder joint was stressed repeatedly under two different conditions. The first condition was given by a load,600 N , which was chosen from the relaxation experiments, and the time at which the solder was not yet relaxed (30 s), see fig 11. The relaxation fatigue time test was carried out at the same load - but at a time after which the solder was relaxed ,3 h, according to the relaxation curve, the relaxation fatigue time test was carried out.

The result is obvious in so far as a much greater number of cycles to fracture (n = 18) could be achieved with the sample which had not experienced relaxation.The sample which could relax totally before new stress was applied on broke already after 6 cycles. This is in good agreement with the rule that the longer the hold time, the lower is the number of cycles to fracture (3). But it is not necessarily the number of cycles to fracture which is the important factor in the fatigue life of a solder joint.If the number of cycles is multiplied by the cycle time we get a far longer lifetime for the sample which cracked already after 6 cycles, namely 18 hours instead of 9 minutes for the sample which broke after 18 cycles.

This consideration is important.If there is the possibility to change the cycle time to longer values - and when speaking of thermal fatigue,there are often such possibilities - you admittedly decrease the number of cycles to failure,but you increase the lifetime of the joint.

In (4) results were given which indicate that a soldered ring pin sample could withstand a larger number of cycles to fracture if the ring and pin were of copper instead of iron. In (5) however results can be found which show that the strength of a solder joint on steel was improved when the sample was aged at 105°C to 155°C over a period of 100 to 1000 hours. The shear strength of soldered copper samples decreased to nearly half the value for an untreated sample under the same conditions. This leads us back to the suspicion which was mentioned that the lifetime could be changed drastically due to diffusion ,when discussing the validity of the general assumption for the prediction of the lifetime.

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SUMMARY

Sufficient reliable information on microsoldered joints is not available today to allow a reliable forecast of the lifetimes to be made (1). This is inspite of the large amount of literature on fatigue problems in solder joints.There is neither a theory on creep and fatigue of solder nor sufficient material data which could form the basis for such a theory. It will therefore remain difficult to make reliable forecasts on the lifetime of solder joints. Much experimental work is still needed to resolve this problem.

But the same problem exists also in other fields of technology. Probably the aircraft industry was the first one to introduce the concept of the analysis of the working conditions in order to investigate the problems for aluminum in aircrafts. In power plants and turbines low cycle fatigue is a problem. Creep and fatigue problems in lead can be found in the chemical,the battery and the cable industry. Until we have sufficient knowledge in our own field of technology we must try to test,to learn by experience and to apply knowledge from other industries to our own problems.

ACKNOWLEDGEMENT

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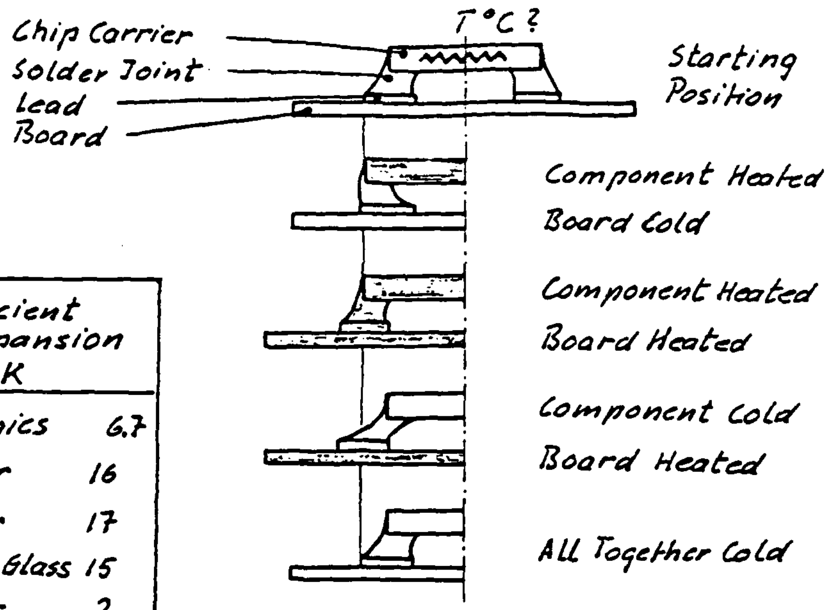
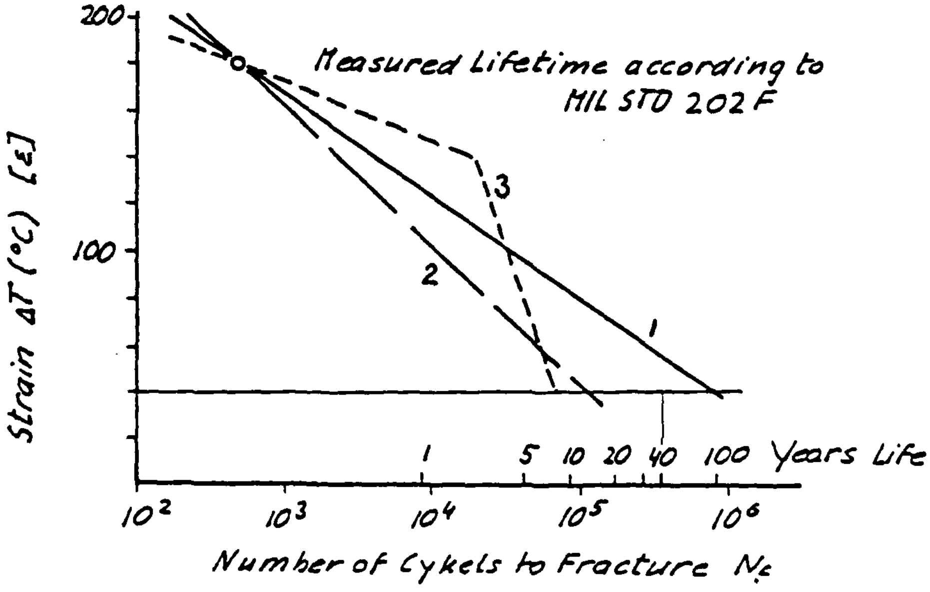
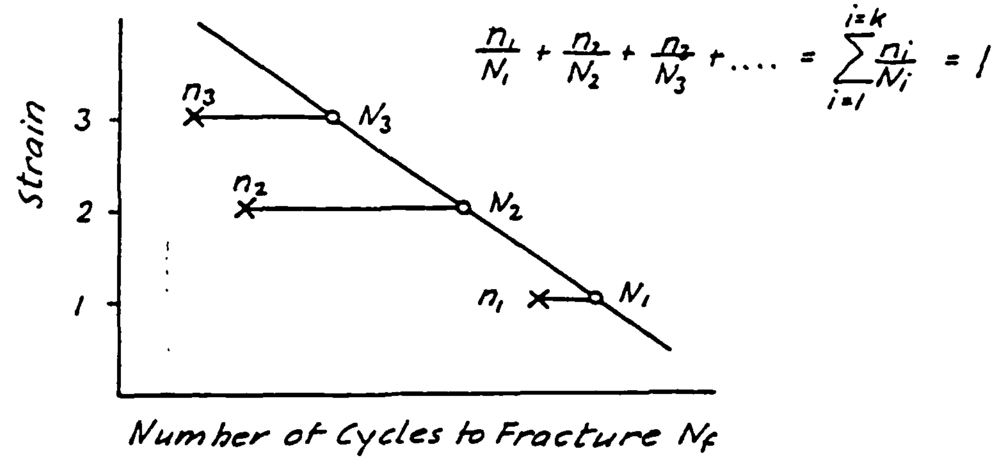


Coefficient of Expansion $10^{-6}/K$	
Ceramics	6.7
Solder	16
Copper	17
Epoxy Glass	15
Invar	2

Stress on a Solder Joint 83 01 01



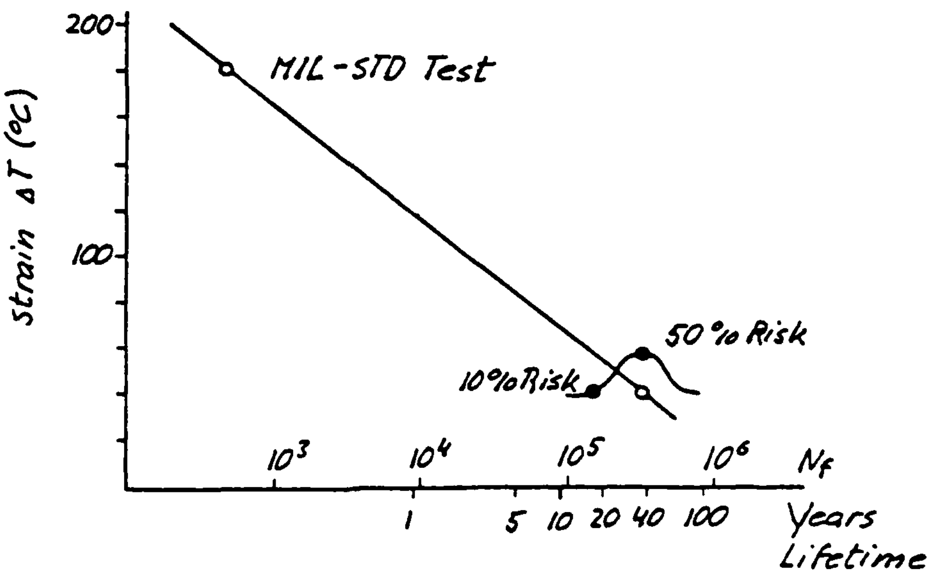
Coffin - Mansons Law 83 01 02



n_1 number of used cycles at strain σ_1
N_1 number of cycles to fracture at strain σ_1

Miners Rule

P30103



Reduction of Lifetime by
Misinterpretation of Results

P30104

$$\Delta \varepsilon_p N_f^{\beta} = C$$ Coffin-Manson Law

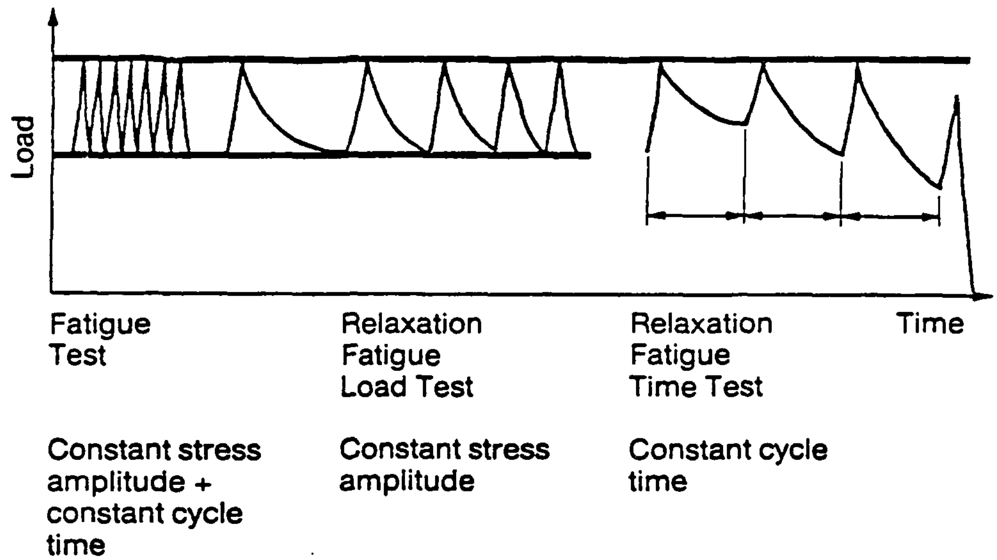
$\Delta \varepsilon_p$ Plastic Strain Range
N_f Number of Cycles to Failure
β, C. Materials constants

$$N_f = \frac{1}{2M}\left(\frac{2h(1+\nu)\ln(1+e)}{r \cdot \Delta T \cdot \Delta\alpha}\right)^{1.67}$$ Taylor et al.

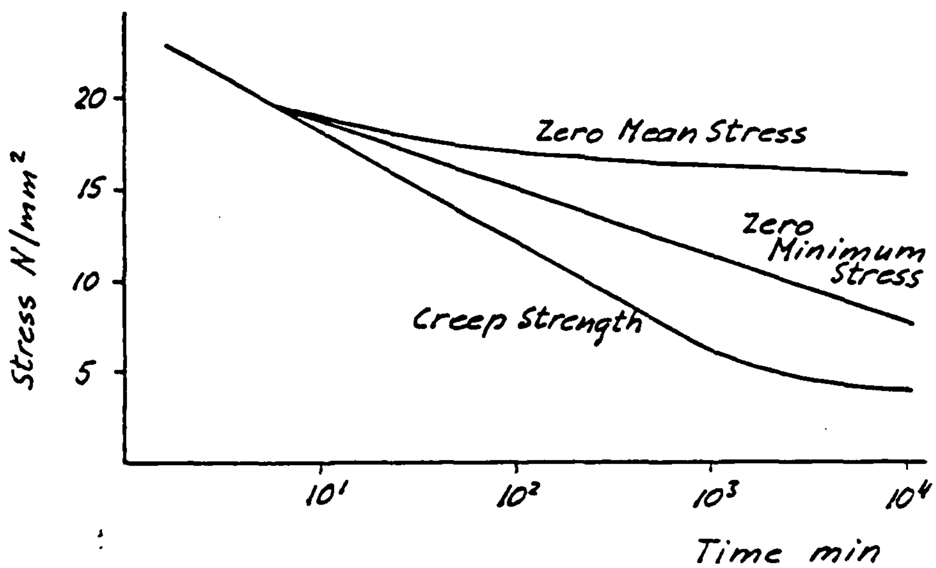
M Empirical Materials Constant
Poisson Ratio
h Heigth of Solder Joint
e Area Reduction Factor
ΔT Temperature Difference
$\Delta\alpha$ Difference Expansion Coeff.
1.67 Material Property

Coffin - Manson Law P30105

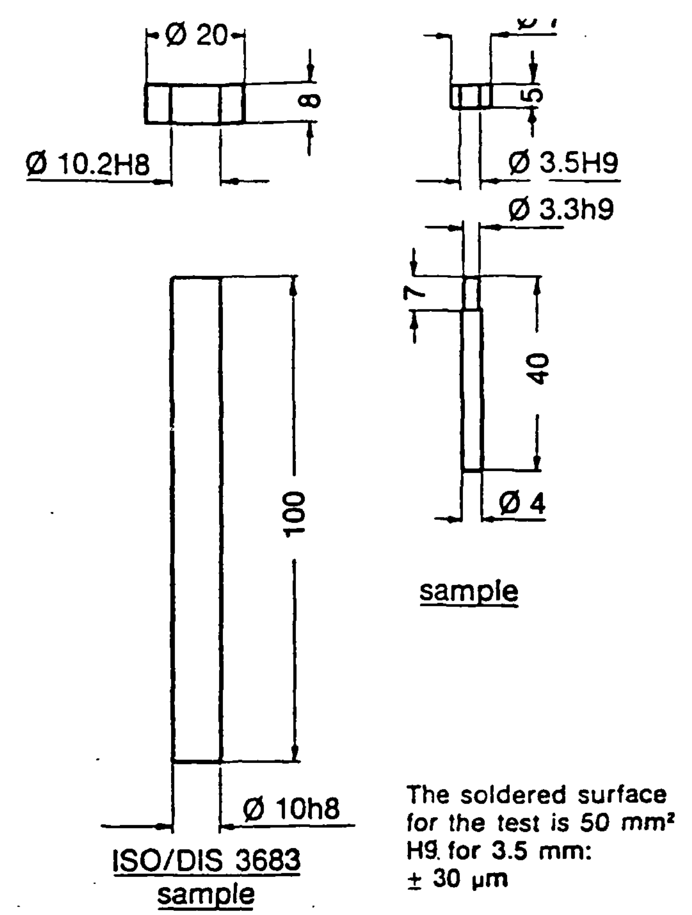
			Cycles
1	**During Production**		
	Cooling after soldering		10
	From 183°C to 20°C	ΔT = 163	
	Repeated at repairs		
2	**Storage and Transport**		
	Thermal cycling between		
	–40°C and +80°C	ΔT = 120	500
3	**Station at work**		
	Day and night cycling		
	Full power during daytime		
	80°C at PWB. Switch off		
	during night 20°C	ΔT = 60	15 000
4	**Operating, Telephone call**		
	On/off cycling of one		
	component. All other		
	at average temperature		
	component 100°C		
	PWB 60°C	ΔT = 40	350 000
	One cycle/hour		



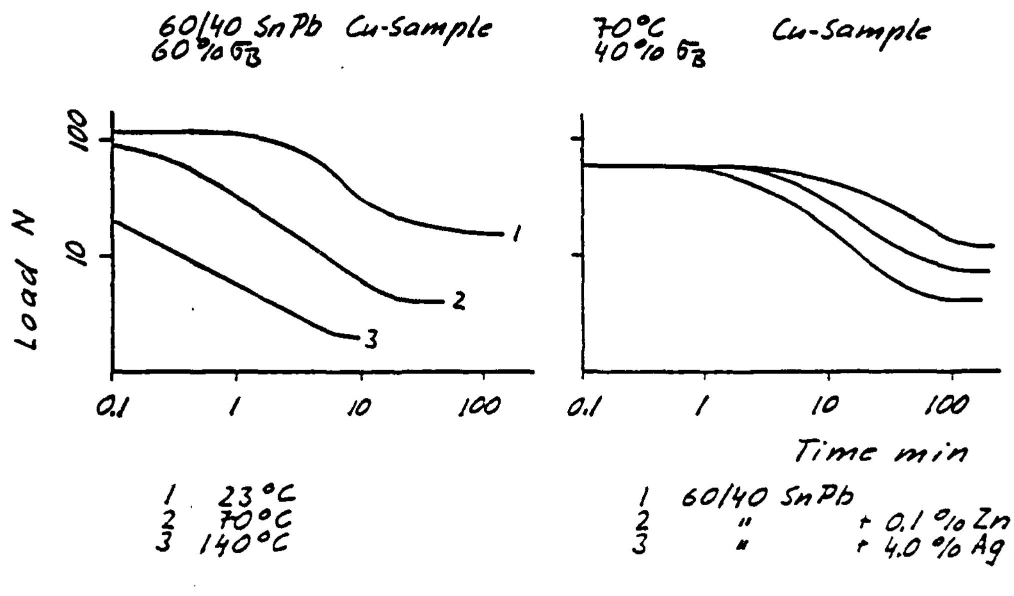
Types of Fatigue Testing 790907



Relation between Different
Types of Fatigue Stress 830108



Sample for the Strength Tests 790909



Result of Relaxation Tests 830110

	Testing Temperature °C 23	70	140	Test Method
60/40 Sn Pb	4.7 years 200 – 11 000	203 20 - 380	1.4 0.4 - 10	Creep Relaxation
" +4% Ag	> 40 years 450 - 18000	2956 9 – 2000	6.8 0.35 - 20	Creep Relaxation
" +0,1% Zn	1.1 5.5 - 10000	157 2 - 300	2.8 0.6 - 40	Creep Relaxation

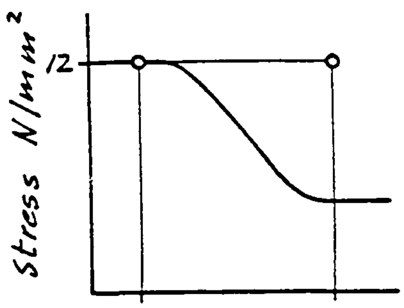
The given values are for

Creep Time to fracture in hours

Relaxation First value Start of relaxation in min
Second value End of relaxation in min

Comparision of Creep and Relaxation 830111

Cu-Sample
70°C



Relaxationtime	30s	3 h
Cykeltime	30s	3h
Number of Cycels to Failure	18	6
Lifetime to Fracture in hours	0.15	18

Fatigue and Lifetime 830112

PARTICLE IMPACT NOISE DETECTION AS A PRODUCTION SCREEN

R.E. MARTIN
GENERAL DYNAMICS
POMONA DIVISION

General Dynamics Pomona Division has recognized from the time it started manufacturing military equipment for the government that part quality and reliability are key factors in the economical production of reliable equipment. This is particularly true of the type of hardware produced at Pomona Division. There is little redundancy - failure of almost any part will cause a degradation of capability and possible failure of the mission. As part of the overall reliability program, parts, particularly semiconductor devices, were procured with full military standard preconditioning and screening and all lot acceptance testing and then retested in-house after delivery. This practice should have provided parts of high quality and long term reliability which could be counted on to have a negligible failure rate in the production process and long life in the equipment after delivery. So - semiconductor parts problems were solved - or were they?

Pomona Division was introduced to the subject of PIND testing rather dramatically about 12 years ago. In final environmental/functional tests of hardware about to be delivered, a small number of failures was encountered. In production terms this failure rate may have been considered normal, but reliability requirements imposed by our customer demanded that each production lot of delivered hardware show a very high yield at final test. We were not quite achieving this specified success rate. Diagnosis of the failures revealed that a significant fraction was due to internal shorts in transistors and microcircuits, caused by conductive particles. This was cause for real concern. These parts had been through screening

equivalent to JANTX or MIL-M-38510 level B. They had not shown up as failures in lower assembly level testing. If some failed at final test of the hardware, there were probably more incipient failures sitting quietly in the hardware waiting to happen. PIND testing was new at that time but it seemed promising. A program of 100% screening of all canned semiconductors was started and was immediately successful. Assembly failures due to conductive particles in semiconductors decreased radically - to an acceptably low level.

It is hard to argue with success, but it is harder yet to leave it alone. The immediate problem had been solved, but as time went by, questions - valid ones - were raised about various aspects of PIND testing. During the initial PIND screening, the percentage of parts rejected seemed inordinately high. It was hard to imagine that all rejections were potential failures. Internal examination of the PIND failures showed, as is well recognized now, that non-conductive particles, which are harmless, can show much the same symptoms in the PIND detector as metallic particles. Size discrimination was poor - a particle too small to cause a functional failure would cause the part to be rejected. The PIND test is not completely precise - some (very few) devices with particles escape - some with no particles are rejected. And, of course, 100% PIND testing adds to the cost of the product.

These factors were debated and evaluated at the time PIND was introduced (1972), and indeed are still being debated. The decision made in 1972, which was, in retrospect the only decision which could realistically be made, was to continue 100% PIND testing in the original program which had triggered the requirement and to extend it to other production programs at Pomona Division. The results of this decision have been good - there have been very few particle oriented failures in production and no field failures traceable to a particle contaminated part.

This is our position at present: 100% PIND testing is performed on all canned devices used in production programs. Scoring and decision making are on a lot basis. PIND testing forms a portion of the overall Pomona Division SCRIP (Semiconductor Reliability Improvement Program) screen. SCRIP consists of the following steps -

- Temperature cycling - 25 cycles

Diodes and transistors	-65°C to +175°C
Microcircuits	-55°C to +150°C
Hybrids	-55°C to +125°C

- PIND
- Electrical test - Room ambient temperature, selected parameters

The PIND testing is performed on standard equipment, subjecting the device under test to a 5g, 30 Hz vibration with a 2000g coshock. Detection of particles is by the standard acoustic method with audible and visual indication to the operator. Since the discrimination of the PIND process is not absolute, the following evaluation and decision making procedure has been adopted -

> If rejects of the first 100% screen are less than .5%, rejects are removed and survivors are released for use. If rejects exceed .5%, survivors are rescreened (100%). If rejects on the survivors are less than .5%, rejects are removed and survivors are released for use. If rejects exceed .5%, the process is repeated. This process will be repeated until the reject rate is less than .5%, up to a maximum of five times. If the reject rate exceeds .5%, on the fifth screen, rejected parts are diagnosed to determine degree of risk in using the survivors (are particles conductive? Are they large enough to cause shorts?) and a decision on useability of the survivors of the lot is made. In addition, if cumulative failures exceed 5.0%, the supplier is notified and corrective action is required.

The SCRIP process is shown diagrammatically in Figure 1.

In the course of 10 years of PIND testing, a very large amount of data has been accumulated. Attempts have been made to analyze this data to determine possible modes and perhaps to understand better how PIND testing should be performed. A sample of six months testing was studied to determine distribution of failures. Figure 2 shows the results of one cut of this data, on microcircuits. The percentage of rejects in each of the lots screened was computed and the lots were categorized in one percent reject rate increments. A lot is defined here as parts of a single date code from a single manufacturer. In accordance with the semiconductor specification, this is assumed to be more or less homogeneous. The total number of parts in each one percent increment was determined and converted to the percentages of the total quantity as shown. Figure 2 represents a total population of about 310,000 parts.

The data shown in Figure 2 are not surprising, but some discussion of them might be in order. First, it is possible, apparently, with good process control, to make parts with no particles. Lots totalling 20% of the total population studied had no particle type defects. The increment with the highest percentage of the population was in the zero to one percent range. This result is as might be expected - normal process control will result in lots with a small percentage of rejects. Above one percent reject rate, the population per increment decreases rapidly but is still significant. This might be considered the area of poor process control. It should be noted that there is a small but significant quantity of parts (about two percent) from lots with a defect rate of ten percent or higher. If it is desired to continue the prior categorization, this defect rate would be the result of an out-of-control process.

Figure 3 shows equivalent data for transistors. The total population shown is 581,000.

The overall average reject rate for the ten years that PIND testing has been performed has been 1.1% for transistors and 1.3% for microcircuits. This has been relatively constant over this period.

These data show "raw" defect rates. It is known that many, or most of the defects observed would not cause hardware failures. However, the defect rate figures shown are at least two orders of magnitude higher than would be acceptable for production if all rejects were truly defective. If a delivered hardware item has 1000 canned devices in it, the presence of even .01% percent actual defective parts (parts having a conductive particle large enough to cause an internal short) would mean that (on the average) every tenth hardware item could have a potential time bomb in it ready to go off at any time. Some of these would be detected during the in-plant environmental screening - some would remain in the hardware item when it was delivered and put into use. From a long term reliability viewpoint, this would mean an unacceptable reduction in the mean time to first failure.

Since the inception of the PIND program at Pomona Division 10 years ago there has been a significant change in the susceptibility of semiconductors to shorts by internal conductive particles. This change is, of course, the widespread use of protective coatings (glassivation) on the surface of the chip. This protective layer eliminates the possibility of shorts due to very small particles bridging exposed conductive paths on the surface of the chip. With a glassivated chip device, a particle must be long enough to touch two internal leads or their exposed pads to produce a short.

While not all PIND rejects are diagnosed, some of them are, and some data is available to estimate the percentage of potential failures. A sample of 482 parts rejected at PIND during 1982 and

diagnosed to determine circumstances of rejection was analyzed. Results of this analysis are as follows:

Total parts delidded and examined	482		
Parts with no particles found		10	
Parts with non-conducting particles		313	
Parts with conducting particles		159	
Parts with conducting particles too small to cause shorts			93
Parts with conducting particles large enough to cause shorts in the device in which they were found			66

Thus, in the sample studied, 66 parts, or 13.6% of the parts diagnosed, had particles large enough to cause shorts. Assuming an average overall PIND rejection rate of 1.2%, about .15% of the parent population would be potentially defective.

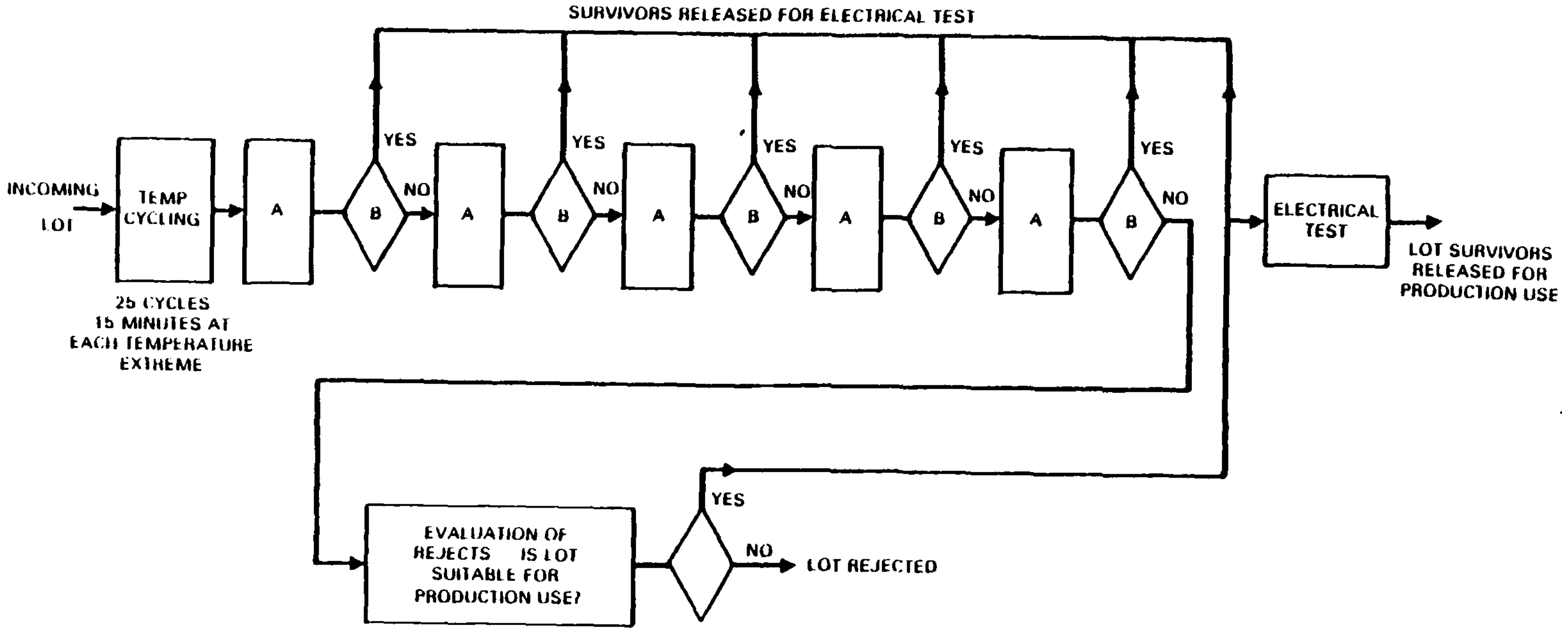
To determine whether the conductive particles found were capable of causing shorts in devices with protected surfaces on the chip, the distribution of size of the observed particles was determined and is shown in Figure 4. While the size of particle capable of causing a short in a device with a protected chip varies with the geometry of the part, there are many device types in which an 8 mil particle can, indeed, bridge the distance between exposed conductors. Thus, those particles shown at 8 mils or above in Figure 4, comprise 28 instances, or 6 of the 482 diagnosed. Assuming an average overall PIND reject rate of 1.2%, these comprise about .07% of the total population. The distribution of these failures among different part numbers and different lots varies widely - many of these potential defectives come from the "out-of-control" area indicated in Figures 2 and 3, but there is no way of telling which part numbers and which lots have a high incidence of large particles without PIND testing.

One reason for our concern is related to the type of equipment we make. Tactical weapons are subjected, during their life, to a continued and varying mechanical (shock and vibration) and thermal environment. A part with a conductive particle will be vibrated, shocked, rotated about all axes, and subjected to radical temperature changes. Any particle in the part will, eventually, assume all orientations and all positions within the part cavity and, if large enough to bridge the minimum distance between exposed conductors will cause a short, either intermittent or permanent. This environment would be significantly different in the case of permanently installed ground equipment. After delivery and installation of the equipment, any particles would rest quietly in a single position within the part cavity and not cause any problem. In this case the evaluation of the need for PIND testing (at least in terms of long term reliability) could be significantly different.

The title of this paper stated that it would discuss PIND as a production screen and it has done just that. We have not been able to acquire detail diagnosis data to quantify precisely the effectiveness of PIND screening - production programs cannot normally afford this type of luxury. We have gone far enough to indicate that, at present, for the type of product we make, it is effective and that it removes potential failures which could have a serious impact on product reliability. This is not to say that we are committed to the present PIND test system or to our present method of using it. The requirement for detecting and removing parts with potential shorts will remain. We would hope that better detection systems will be developed, such as an actual short indicator rather than a particle detector. This would minimize the number of perfectly usable parts which are rejected because we don't know with certainty that they will not exhibit a short at some time. We would hope,

without too much optimism, that suppliers will improve their process control to reduce or eliminate the presence of any particles. A system for complete insulation of the interior of the device would remove any possibility of a particle causing a short. We would like to see these things happen and when and if they do our methods of dealing with internal particles will change. Until then, we will continue our present system as a practical method of removing a reliability risk in our delivered products.

16c



A 100% PIND TEST 5 g, 30 Hz, 2000 g COSHOCK

B IS REJECT RATE LESS THAN 5%?

A105389 813

FIGURE 1. SEMICONDUCTOR RELIABILITY IMPROVEMENT PROGRAM (SCRIP).

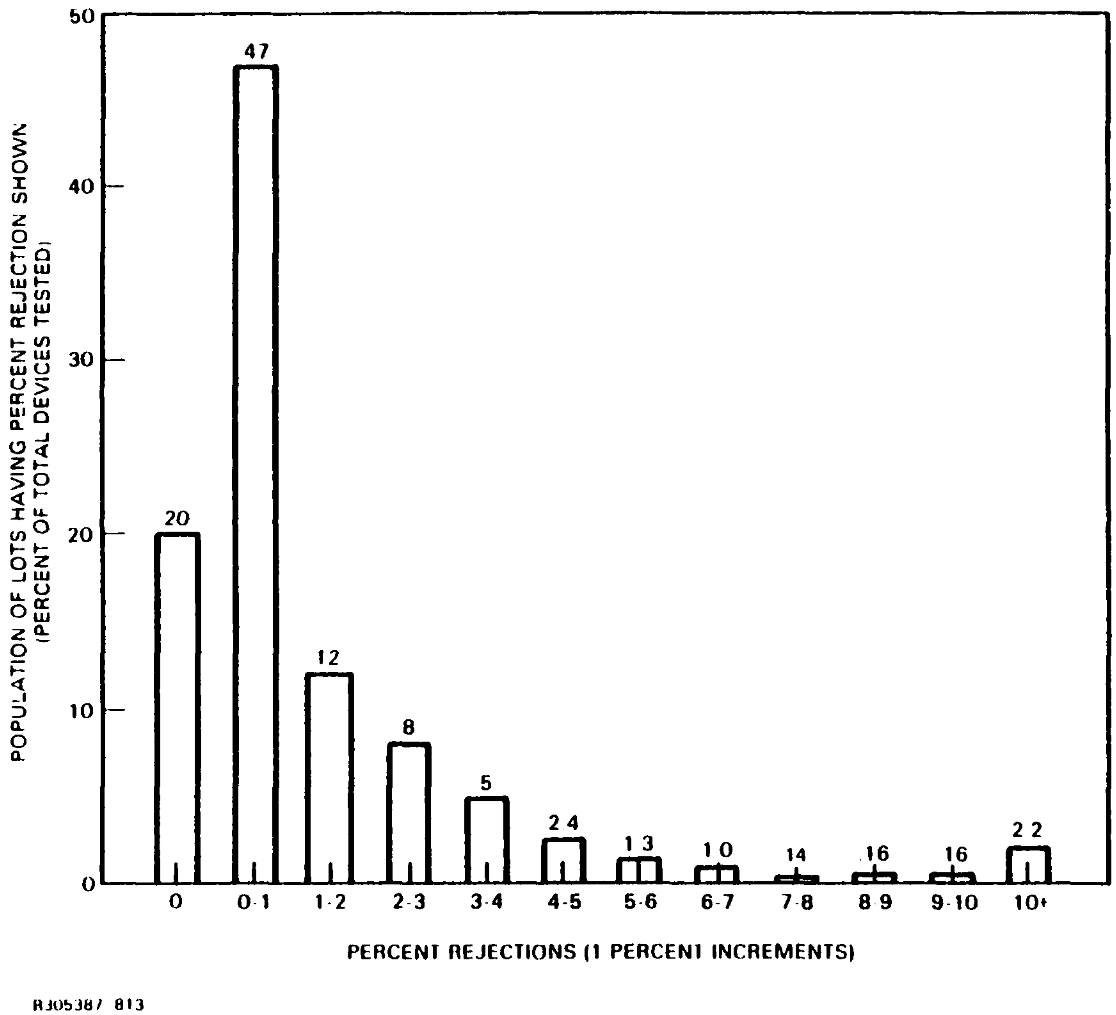


FIGURE 2. DISTRIBUTION OF PIND REJECTS (MICROCIRCUITS).

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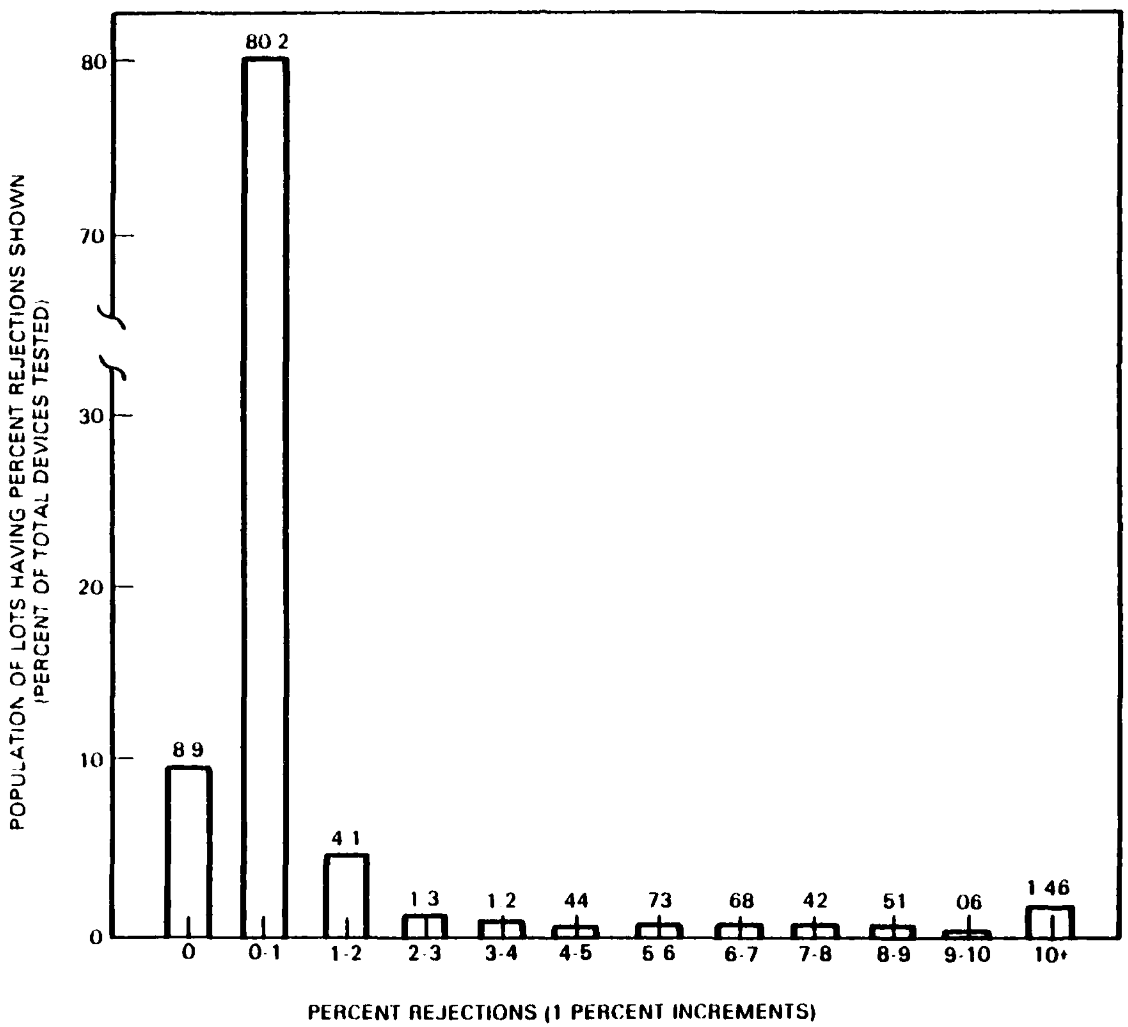

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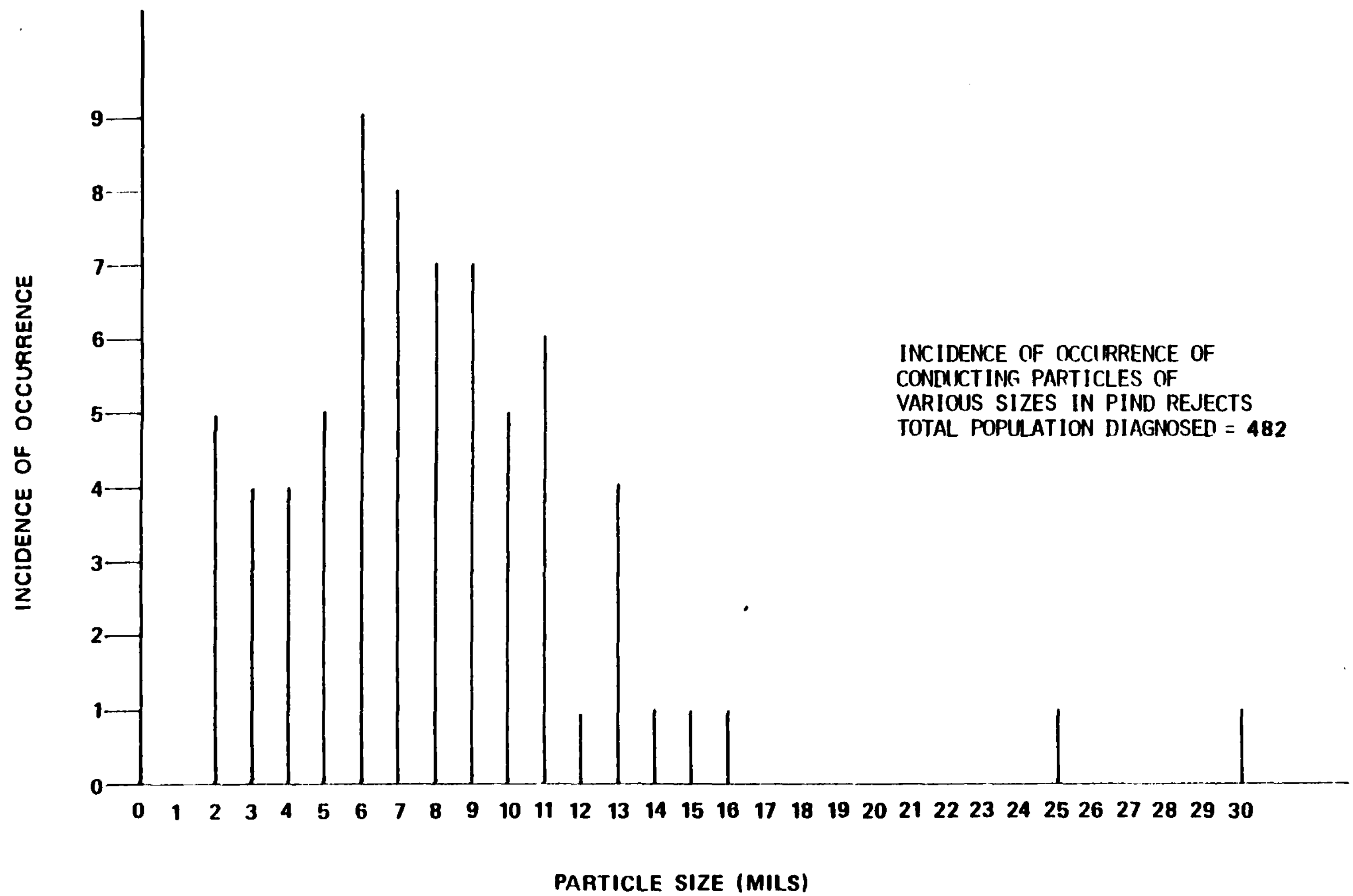
FIGURE 3. DISTRIBUTION OF PIND REJECTS (TRANSISTORS).



INCIDENCE OF OCCURRENCE
PARTICLE SIZE (MILS)
0 1 2 3 4 5 6 7 8 9
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
INCIDENCE OF OCCURRENCE OF
CONDUCTING PARTICLES OF
VARIOUS SIZES IN PIND REJECTS
TOTAL POPULATION DIAGNOSED = 482

FIGURE 4

ROBERT E. MARTIN

Mr. Martin received a B.S. degree in Electrical Engineering from Columbia University in 1943. From 1943 to 1946 he served as an electronics officer in the U.S. Navy. In 1947 he joined the staff of the Naval Research Laboratory as a Radio Engineer. From 1948 to 1961 he was at the Naval Applied Science Laboratory, in charge of all activities on vacuum tubes and, later, on semiconductor devices. Mr. Martin spent the next two years with Amalgamated Wireless of Australasia, developing a line of portable modular test equipment. In 1963 he joined the Component Engineering Section of the Pomona Division of General Dynamics, later becoming head of that section, in charge of selection, documentation, qualification and reliability of all electronic and mechanical parts used in the division. In 1972 he became head of the reliability activity for the Sparrow (AIM-7F, AIM/RIM-7M) program, a position which he still holds. The reliability program for Sparrow includes parts engineering and reliability as well as failure recurrence control and assembly stress screening and reliability demonstration.

PARTICLE IMPACT NOISE DETECTION

IN DEVICES WITH INTERNAL CAVITIES

Written by:

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Note: Particle photographs are copyrighted by Aviation Week and Space Technology, April 11, 1977, where indicated.

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PARTICLE IMPACT NOISE DETECTION IN
DEVICES WITH INTERNAL CAVITIES

1. Why Particle Impact Noise Detection?

It wasn't long after the start of the industrial revolution that man found out a "monkey wrench" in the gears effectively stopped the machinery. As ways were found to reduce size and improve performance of equipment, loose nuts and bolts were also very effective in producing damage. New techniques that removed some problems, created new disasters with weld flash and splatter. All of this pales before the problems of today's particle contamination scale of size failure modes. We are now capable of destroying a 10 million dollar space vehicle with a conductive particle with the mass of a one thousandths of an inch diameter gold ball. How do we find a high percentage of these possible failures? With a Particle Impact Noise Detection (PIND) test that is capable of detecting the equivalent mass of an unrestrained (loose) one thousandths of an inch diameter gold ball.

2. A General History of Particle Impact Noise Detection (PIND) Testing

It appears that in the early 1950s some companies, such as G.E., Lockheed, McDonald Douglas and agencies such as NASA and NBS tried some method of particle detection on electro mechanical relays, a device ideally suited to random failure due to particulate contamination.... a device however, that did not readily lend itself to particle impact noise detection due to movement of mechanical parts designed to move, and total failure if a soft piece of insulation lodged between the contacts. The trials and tribulations of vendor versus customer in this area are legend. Enter the solid state devices.... with a few exceptions, if loose particles could be found in the cavities of these components, a major failure mode could be diverted. The April 11, 1977 issue of Aviation Week and Space Technology reported in detail the findings to that date of this problem. Included here are copyright photos taken of typical particles such as caused catastrophic failure of space vehicles. Detection of such particles is what PIND testing is all about.

Figure 1

Loose conductive particle wedges under 1-mil-dia. wire bond.

Figure 2

Loose particle of conducting material (arrow, right) is wedged under wire lead on glassivated microcircuit making contact with exposed silicon in scribing grid and causing short circuit. Particle of this type may go undetected during manufacture, then break loose during circuit's exposure to severe vibration.

Figure 3

Loose particle (white material) shorted this microcircuit (left) between wire lead and scribing grid on chip. Note white material is not continuous, indicating that it melted when short circuit occurred, causing momentary failure.

Figure 4

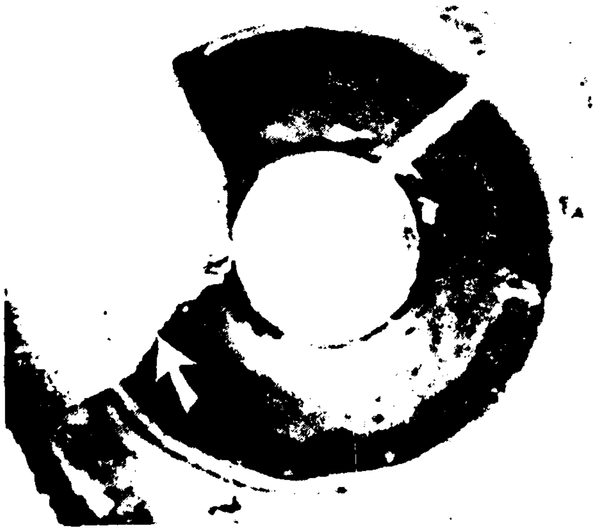


Figure 5

Small piece of semiconductor die lodges against bonding post on a transistor (above, left), thereby shorting device. Long sliver of gold eutectic material (arrows, above), roughly 40 mils long, shorts lead to header.

3. What Items can be PIND Tested?

In general, components with internal cavities that do not contain loose or moving parts as a function of their use can be tested. If the loose or moving function should not occur under the mechanical stimulus of the PIND test even these can be tested. Difficult parts to PIND test are components that externally flex or resonate mechanically during the test. A need for special support or temporary "potting" of such devices may be required. This will be covered in more detail under "Device Under Test Evaluation".

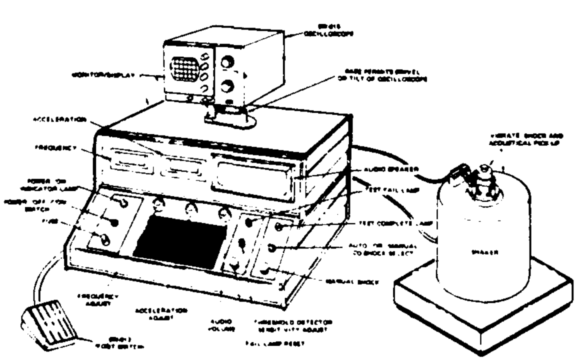
4. What Items Cannot be PIND Tested Effectively?

Components with loose or moving parts as a required function of operation will produce apparent noise difficult to separate from particle noise. Although a "signature" of these movements not related to particles may be used to help identify good parts, it is seldom repeatable to the assurance level required to preclude accepting some with particles. Components with dimensions in excess of 4 inches in any axis, or those not hermetically sealed or of flimsy construction will present a significant mounting problem on the PIND test equipment.

5. What is a PIND Tester?

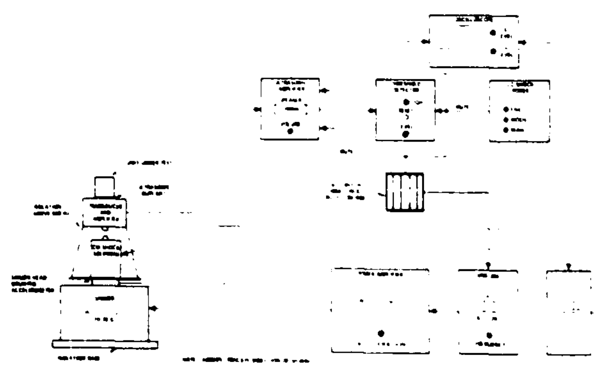
A general description of the type of equipment that has been developed to detect loose particles in solid state devices with cavities consists of an ultrasonic microphone (transducer) that is mounted on a physical stimulator, and the necessary detection circuits to hear, see, and electrically announce the presence of a loose particle in the device under test (DUT). The physical stimulation consists of a

Figure 6



Particle Impact Noise Detection Test Set

Figure 7



PIND Block Diagram

shock pulse before and during the application of sine vibration to the device under test, which is mounted directly on the diaphragm (or platen) of the ultrasonic microphone by a viscous couplant. In some instances, adaptors must be used to allow mounting of the DUT to the microphone. These are usually made out of aluminum and are designed for minimum loss of the particle signal. The adaptor fit to the microphone and the DUT fit to the adaptor rèquire a viscous couplant interface. A new technique uses a wax like material that is cast in a block around the DUT before test. One side of this block is then coupled to the microphone platen with viscous couplant and the particle sound is transmitted through the waxy material for detection. Figures 6 and 7 show typical PIND test equipment and a block diagram of the interconnections and controls.

6. Development of a Particle Impact Noise Detection Test Method

Faced with certain knowledge that PIND testing was a way to detect loose particles in solid state devices with cavities, NASA contracted with McDonnell Douglas to develop the specifications and test method best suited for such detection. This study produced the essence of MIL-STD-883, TM2020 which cites the shock level, shock duration, vibration level and vibration frequency, the timing sequences of these stimuli, the accept/reject criteria, and much more. Over a period of years, the capture rate of the test has been abrogated to less than that of the original by industry and equipment manufacturer instigated changes on loose particles smaller than the equivalent mass of a two thousandths of an inch gold ball. Loose particles above this size are probably captured at the same rate as the original test method. Since TM2020 is considered a non-destructive and repeatable test, it is imperative that the Device Under Test not be subjected to stresses during the PIND test that exceed its environmental capability. These are mainly in the realm of shock and vibration, with the vibration component rather simple to analyze from a metrology standpoint. In fact, an optical wedge properly designed to comply with the formula $G=0.0511 \times HZ^2 \times D$ (where G= acceleration in peak gravities, HZ= frequency of vibration, and D= displacement in inches) can be used from 40 to 100 hertz with an accuracy equivalent to the NBS measurements. This is not true of the pre test and co test shock pulses. Measurements of these should use equipment and techniques called out in a memorandum from the Defense Logistics Agency, Defense Electronics Supply Center, Ref. #DESC-EQM-80-393 (Mr. Fischer/513-296-6355/mkc) dated 10 April 1980.

It is well to remember that TM2020 is an empirically derived test, the validity of which is supported by test data generated during its construction. Unless the user is prepared to defend modifications of this TM with substantial test data, it is well to approach such modifications with caution.

Now that the PIND test equipment and the PIND test method have been discussed, we will address the successful installation of a PIND test program in your facility.

7. Selection of Equipment

First of all, it should be obvious the equipment you select or build must be capable of conforming to the requirements of the contractual obligations of your commitment. If this is MIL-STD-883, TM2020, then be sure to purchase or build equipment that can be qualified to this standard. In this area it is well to consult your metrology department if one is available, or otherwise convince yourself that the purchased equipment is adequate. This is frequently done by contact with a company using PIND testing who has qualified his facility to the test method. A manufacturer of such equipment can generally supply information which you can verify.

Other consideration of equipment selection might be manufacturer support after purchase, ease of calibration and adjustment, available options, such as dedicated work

benches, vibration shaker isolation devices, R.F. screen boxes to reduce radio frequency interference, reduction of the magnetic field at the device under test location, completeness of the metrology manual supplied, and other items to make PIND testing as effortless as possible. It is recommended you buy a tester that does not inhibit your ability to modify your PIND tester to vibrate at 27 hertz for testing small electro mechanical devices. Recent tests on devices weighing 3 to 4 pounds and vibrated at 3 Gs, 27 hertz, with special fixturing, has found #2 lock washers detectable as loose parts, or, to say it another way, be sure the equipment you buy is flexible enough for a growth in PIND testing to other components you may use or fabricate in the future.

8. Test Facility Location

Every effort should be made to place the PIND test equipment in an acoustically quiet location, essentially free of R.F. noise. A radio frequency screen room is ideal, but in most cases, not practical. An assessment of the R.F. problems involved is relatively simple. Obtain a portable radio that covers the "long wave" band of 150 to 400 kilohertz. Tune it to 150 kilohertz and explore the area of your choice. The quieter the location, the less prone to cause trouble during testing. Extremely poor conditions will require isolation transformers, filters, and an R.F. screen enclosure. Even with this equipment, it may be well not to PIND test in the middle of a thunderstorm. Static electricity can also be a source of false failure indications and should be eliminated by floor grounding pads.

Remember the test method requires the test operator to observe an oscilloscope, listen for particle noise, and fail the DUT if the particle annunciator activates. This requires the equipment location to be relatively free of distractions such as traffic and environmental anomalies. Sufficient adjacent room should be available for incoming parts and outgoing parts, and if possible, clean box storage of these if the parts are clean on entry into the area. It is suggested a stereo microscope of at least 20 power be available close to the PIND work station to verify external cleanliness of the DUT if required. Restricted access to the PIND work station is recommended. Use of the PIND tester by qualified personnel only is highly recommended.

9. Where Should you Apply PIND Testing?

The product manufacturer can apply this type of test in his production process to help determine weld schedules, sealing techniques, cleaning processes and other means of controlling contamination. Once the best way is established, he can control it with PIND testing by using the test as a production tool. With special designs, he can decontaminate parts immediately prior to final seal by vibration and ultrasonic detection to insure the particles are removed or no longer mobile - then effect the final seal - usually a small hole in the case or cover.

It seems that one of the major contributors to particulate contamination involves thermal shock, therefore PIND testing after thermal shock exposure could help determine if the materials used and processes employed are in fact acceptable for the thermal exposure required.

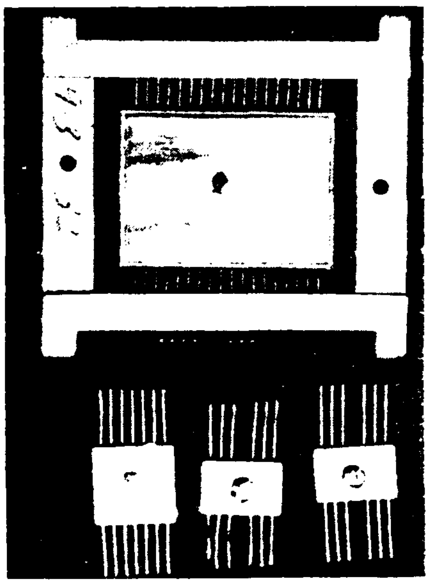
At final "buyoff" of the parts, the tests should be conducted strictly to spec. You may find it worthwhile to consider a shorter time interval between co test shock pulses for other than the final buyoff point. Test Method 2020 requires about 1/2 minute of test and handling time per part. If the shock pulses are changed to once a second, almost 6 parts a minute can be tested. In addition, you can test multiple parts by casting them in a "puck" of paraffin or Cetyl alcohol. This can also be used to test multi-lead devices in their plastic handling carriers. The Cetyl

alcohol traps the leads while allowing good transmissability of 150 kilohertz signals from loose particles to be detected.

Figure 9 covers the broad field of particle removal and suggests how PIND testing can be employed in the production phase to reduce particles and in the test phase to accept the product.

Figure 8 shows a typical flat pack IC that would lend itself to the potting technique described above.

Figure 8



Parts Adaptable to Potting in Cetyl Alcohol

Figure 9

TECHNIQUES TO REMOVE PARTICLE CONTAMINATION AND CONTAMINATED PARTS

1. Visual inspection and removal by hand
2. Area control, dry nitrogen blowoff, visual inspection
3. Area control, dry nitrogen blowoff, visual inspection, vibration and shock stimulus (PIND)
4. Use of PIND equipment –
   A. Prior to final lidding
   B. Prior to final seal with escape hole in lid
   C. After final seal with "getter" material in enclosure
5. Final X-ray (detection limited to .003 inches X-ray opaque material)
6. Final PIND test (detection limited to mobile particle equivalent to .0001 inch diameter gold ball)

10. Device Under Test Evaluation

Although not specifically required by the test method, it is recommended that two samples of any device tested be used as check units. One of these should be known free of particles (fill with silicon grease, or use sticky back tape), the other should have seeded particles of the type expected to be most prevalent in the package. The seeded particle should be of minimum size. These two samples should be used to evaluate the mounting means, confirm the vibration frequency to be used, and hopefully identify noises generated by other than loose particles such as terminals, etc. Although not fully confirmed, we have seen indications the frequency versus internal free package height chart of TM2020 is not valid for other than metal cases. All devices to be tested should be visually inspected for cleanliness immediately prior to the PIND test. A cleaning station should be provided and at least a 20 power stereo microscope are required to eliminate failures due to external contamination.

11. Metrology Considerations

The equipment should be supplied with adequate metrology instructions for proper calibration of the system. Care must be taken that the test equipment does not generate spurious signals, either through signal construction or ground loops. Most frequency counters generate some level of such signals, and may need to be disconnected from the test system during sensitivity or threshold level measurements. In general, if the test equipment increases the noise level, audibly or visually, this condition must be cured prior to calibration of the system. Sometimes this means isolation of the test equipment from the A.C. main power source.

A list of the necessary calibration points has been compiled, which includes the type of test equipment required and the tolerances expected of the equipment. A recommended calibration cycle is included. The main calibration functions are as follows:

Oscillator/Amplifier Control of Vibration Shaker
- Frequency readout
- Acceleration readout
- Overall distortion

Oscilloscope Presentation
- General

Co-Test Shock and Ancillary Functions
- Level and duration of shock
- Muting of audio and threshold detection

150 Kilohertz Presentation
- Amplifier Bandwidth
- Overall gain and noise level
- Adjustment of threshold detector

Sensitivity Test Unit and System Check Out
- General

PIND Calibrator, BW-012
- General

Co-Test Shock Control
- Timing function

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12. PIND Test Systems Oriented Failures

Each system manufacturer has his own assortment of failure mechanisms, however there is similarity in the problems they encounter. For instance, the vibration stimulus must be capable of rated output over the frequency range without generating spurious noise. Such noise is primarily mechanical in nature and includes cable noise, loose connectors, etc. Preamplifiers and low impedance output, from the platform supporting the device under test, can reduce this problem. Tramp iron particles in the vibration shaker magnetic gap can cause electrostatic, mechanical, or electrical shorting of the voice coil, thus creating noise. These are usually identified as being related to the excursion of the shaker armature, with the greater excursions causing most of the problem.

A system problem related to the power source may appear as spikes on the oscilloscope without any physical stimulus having been applied. This can usually be cured with an isolation transformer and/or additional filters at 150 kilohertz. Technicians familiar with R.F. interference problems should be consulted if these problems persist.

Acoustical input at 150 kilohertz must not be overlooked, however, the ultrasonic microphone employed has a narrow angle of acceptance which is vertical to the platform where the device under test is mounted. These microphones have not exhibited any unusual sensitivity to normal test lab noise levels. It is true that keys jingled over the microphone, or fingernails snapped can produce a failure indication. We suggest you install the equipment in such a manner that such extraneous noise sources will be held to a minimum.

13. Operator Considerations

The operator is required to monitor both the audio and visual displays for particle detection. A fair degree of dexterity is also required to ensure proper placement of the device under test on the mounting surface. Flat surfaces, approximately the diameter of the mount, are the easiest to install, however there is some indication that unless the device under test is embedded properly in the viscous couplant, the first co test shock may burst a trapped air bubble, thereby causing a failure indication. Small parts with slightly rounded surfaces are very difficult to properly mount since they tend to find the "best fit" when vibrated and shocked. Any such movement can generate a noise that will trigger the failure indicators.

The operator's comfort must be considered when setting up the work station, particularly when the test is to be run on large batches for extended periods of time.

An ongoing failure analysis program is of the utmost importance in operator training.

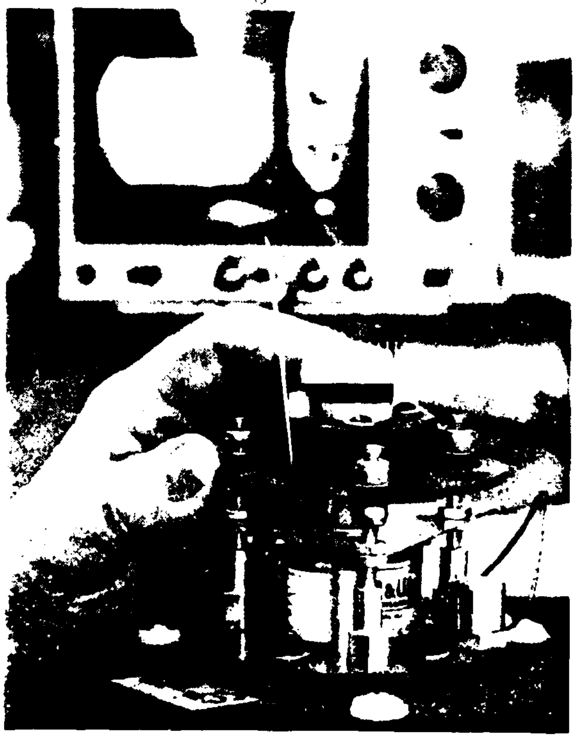
Figure 10

Equipment Setup

Figure 11

Application of Couplant

Figure 12



DUT on Test Fixture

14. Observation of Available Data

PIND testing is not an exact science but is certainly no longer an "Art". The creditability of data points has been masked in various reports and papers due to inconsistent particulate control of seeded samples, variables in different manufacturers' test equipment, and, as cited in one report - operator variables. In one report where 198 "seeded" samples were used, 66 of the group were never found defective during any test, at any time. When you eliminate these from the "seeded" group, instead of a defect capture rate of 55%, our average jumps to 82.5%. In addition, no one has ever determined the number of parts PIND tested and found good which later failed in electrical inspection due to the fact the PIND test lodged the particle where it could be electrically detected.

15. Recommendations

As manufacturers of PIND test equipment, we have been able to see both sides of the coin - the parts vendors viewpoint and the users viewpoint as regards reliability of the end product, and incidently the economics of the end product. We suggest consideration of the following modifications to MIL-STD-883, TM2020 as indicated in Figure 13.

Figure 13

MODIFICATIONS TO MIL-STD-883 TM2020

1. A single strike should not fail any part.
2. Multiple strikes should fail any part.
3. All parts should be tested at the maximum levels that will not cause damage.
4. A repeated failure indication shall cause failure and rejection of any part.
5. Special parts with difficult mounting surfaces should be considered for special test parameters.

REDUCING THE SOLDER DEFECT RATE ON PRINTED WIRING ASSEMBLIES

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ABSTRACT

An experiment was run on a production release of 110 PWA's to determine if the number of solder defects after wave soldering could be substantially reduced by ensuring that all parts had high solderability. The results of the experiment confirmed the value of solderability management. However, an equally significant result was a recognition of the importance of developing better definition of the solder defects and their causes, of which poor solderability is just one. Without this definition, reported values for defect rates, in this study or any other, cannot be meaningfully interpreted or compared. For this reason we discuss not only the experiment itself but also, in some detail, solder defects, their causes, and the evaluation process used to find and tabulate them.

For the experiment, parts were pretinned and inspected for solder coverage; they were retinned as necessary to obtain good coverage. To enable comparisons, the component lots were split in half, with one half-lot tinned, and the other untinned. Each PWA was evaluated before touch-up by a manufacturing operator and by an engineer. The solderability-related defect rate was, as expected, substantially lower for pretinned leads than for untinned leads -- a rate of 0.027% versus 0.102%.

In addition, there were two other larger contributors to the reported defect rate: process-related defects, and faulty evaluation. The major process-related defects were found to be insufficient flow through plated-through holes, excess solder, bridging, insufficient flux, and no solder. Together these accounted for most of the defects that were seen -- an average of 13.7 defects per board, for a per-joint rate of 0.52%. It was found that the manufacturing evaluators were marking as defects many joints which were non-ideal but not defective. Over 10 joints per board, average, were so marked, meaning increased touch-up expense and loss of feedback of information for process control.

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It was found that nearly all of the process-related defects could be eliminated without a major investment of time or money. For example, the cases of insufficient flow were found to be caused by the method used for tack soldering. At our suggestion, this method has now been changed and this defect is not being seen. We also recommend:

- Monitoring the wave soldering operation to ensure that every point on every board is exposed to flux and solder.
- Cleaning the boards in an in-line defluxer with high-pressure sprays to minimize the risk of any solder balls.
- Clarifying the definition of excess solder on the solder side of the board so that only joints at risk are counted and touched up.

To assure the accuracy of defect rate reporting, we recommend:

- Preparing and maintaining a document which more clearly covers every kind of solder defect.
- Maintaining an evaluator training program.
- Auditing the evaluated boards.

For dealing with the problem of poor solderability, we recommend:

- Instituting a plan for selected-lot solderability testing of incoming PWB's and components (instead of universal pretinning).

We believe that if these recommendations were implemented, the defect rate would be so low that 100% evaluation and touch-up could be eliminated.

I. INTRODUCTION

A printed wiring assembly takes only a minute or two to wave solder but an hour or more to inspect and touch up. For many kinds of defects it is necessary to scrutinize a non-ideal joint to determine if it is bad enough to warrant rejection. This is particularly true for cases of poor solder wetting.

If most boards could be made defect-free, they would not require touch-up, and they would take much less time to inspect. In fact if the defect rate were low enough, a good case could be made for eliminating the one hundred percent inspection now required by the customer.

How low is low enough? If we establish a goal of a ninety percent yield of defect-free boards, then for a board with one thousand holes (two thousand joints), the target rate would have to be fifty defects per million joints. This is far lower than the rates being reported by most manufacturers of military PWA's. In order to reach such a goal, it is necessary to understand the cause and cure of each type of defect.

The experiment described in this paper was aimed at reducing the number of poor wetting defects. One common approach to this problem is to change the wave soldering process by using a highly active flux. There are three problems with this approach. First, our customer does not allow it. Second, residues of more-active fluxes are known to cause corrosion. Many board designs do not allow adequate cleaning to insure that all flux residues have been removed. Remaining residue could cause problems with conformal coating and corrosion. And third, even very active flux can't correct all cases of poor solderability.

The other way to prevent cases of poor wetting is to leave the process the way it is but ensure that the component leads and the board are highly solderable before assembly. It was to evaluate this latter approach that the experiment was conducted. The goal of the experiment was to demonstrate a marked reduction in the number of reported cases of poor wetting by using highly solderable parts, i.e. to show the benefits of solderability management.

II. EXPERIMENT

Selection

For the experiment, a production release of 110 boards was selected. This multi-layer board has a bonded heat sink and a good mix of parts: 203 wave soldered components, 75 different item numbers of 14 different types. Table I shows a listing of each component by item number and type. (A further explanation of Table I is given later.) Components for 55 of the boards were to be checked to ensure high solderability, while those for the other 55 were to be used as-received as a control, and the resulting solder defect rates compared.

Pretinning and Inspection

One way of ensuring high solderability is to use a solderability tester. Such a machine has just been delivered to our plant; it was unavailable at the time of the experiment. The other method is to pretin and then inspect for solder coverage. (These two methods are compared in Section IV.) Coupons representative of the printed wiring boards were wave soldered and examined to verify good wetting. The component leads were pretinned by dipping in RMA flux and then in eutectic solder at 500°F for three seconds.

Since it is known that stand-up capacitors have poor solderability next to the body of the component, these parts are routinely pretinned automatically by a special tinning robot. For this reason, all rather than half of the standup capacitors were pretinned. As can be seen in Table I, there were 53 of these per board. Parts which could be held magnetically (Kovar leads) were tinned semi-automatically by tinning operators who manually placed the component on a machine which controlled the dipping. Copper-leaded components were held with tweezers and tinned manually. Another twelve parts were not tinned at all.

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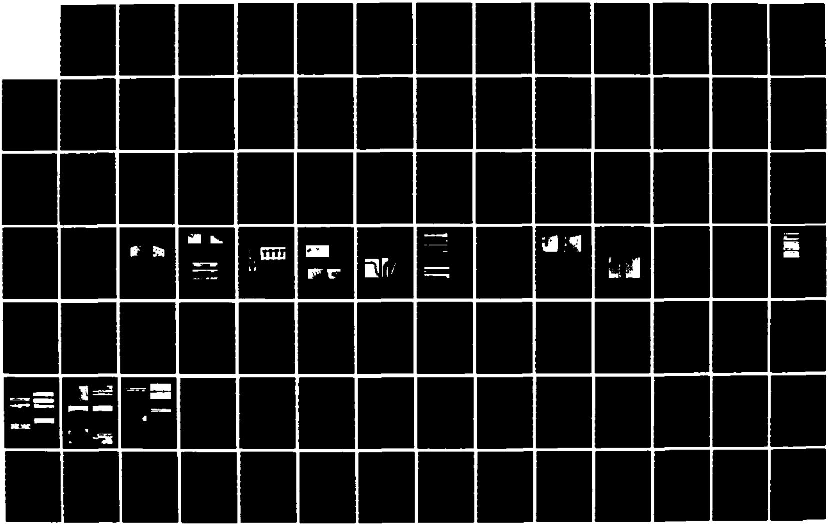

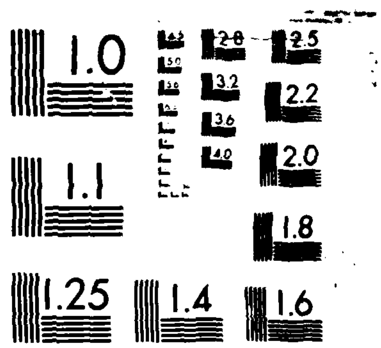

MICROCOPY RESOLUTION TEST CHART

TABLE I

SUMMARY OF PARTS, TINNING, AND WETTING DEFECTS AFTER WAVE SOLDERING

Parts List Item No.	Description	Qty	Leads	Tinning	Poor Wetting Incl. Holes Defects/Leads Untinned	Poor Wetting Incl. Holes Defects/Leads Tinned
27	Stand-up	1	2	x	NA	2/162
28	Cap*	1		x		1/162
29		4		x		1/648
33		2		x		
34		2		x		3/324
35		2		x		1/324
36		7		x		5/1134
37		27		x		3/4374
38		3		Retinned		
97		2		x		
105		2		x		
		53				
31	Axial Cap*	2		28/110 Retin		
32		2		x		
39		19		Retinned	30/1558	7/1520
		23				
40	Variable Cap*	2	3	Not Tinned		NA
41	Axial	4	2	x		
91	Diode*	3		x	1/246	
101		2		x		
		9				
92	TO-18 Diode	4	2	x		
42	Diode	2	4	Not Tinned		NA
107	Bridge	1		Not Tinned		NA
		3				
45	Axial* Resistor	4	2	x		
46		4		x		
47		1		x	1/82	
48		1		x		
		2		x		
50		2		x		
51		2		x		
52		1		x		
53		3		x		
54		1		x	1/82	
55		2		x		
56		2		x		
57		2		x		
58		1		x		
59		1		x		
60		2		x		
61		2		x		
62		1		11/55 Retin		
63		2		x		
64		3		x		
103		2		x		1/160
104		2		x		
		43				
43	Power**	1		x	9/82	
44	Transistor	1		Retin	13/82	
		2				
80	Round**	2	9	x		
82	Can	3		x		
		5				
93	Wire*	[illegible]	[illegible]	Not Tinned		NA
98		[illegible]	[illegible]	Not Tinned	1/324	NA
		[illegible]				
89	Side-Lead	[illegible]	20	Retinned	1/1600	
109	Hybrid	[illegible]		Retinned		
		[illegible]				

Parts List Item No.	Description	Qty	Leads	Tinning	Poor Wetting Incl. Holes Defects/Leads Untinned	Poor Wetting Incl. Holes Defects/Leads Tinned
66	DIP	1	14	x		
74		1		Retinned		
76		3		x		
85		1		x	2/560	
67		2	16	Retin SRA	2/1280	
68		7		Retin		
69		3		Retin		
70		1		Retin		
71		3		x		
72		3		x		
75		1		Retin		
77		4		Retin one date Code 20/220		
78		1		x	1/640	
79		2		Retin		
81		1		x		1/656
83		2		Retin		
84		3		x		
86		1		Retin		
87		2		Retin SRA	46/1280	2/1312
88		2		x		
65		2	24	x		
		46				
73	Rectangular	1	24	x		
90	Can**	2		x		2/1968
		3				
2	Connector	1	90	Not Tinned	1/7290	NA
		203	1299 leads per bd.	Retinned 46.8	108/52733	29/52486
				191 = 25%	0.20% = 2000 ppm	0.055% = 550 ppm

*These parts have copper leads

**Tack soldered on solder side of board.

x Satisfactory solder coverage after single-dip tinning.

41 boards had all DIP's and stand-up capacitors tinned; other parts untinned.
40 boards had all parts tinned except DIP's and parts marked "not tinned."

Nonideal wetting not reported.

Significant reduction in incidence of poor wetting for pretinning items nos. 39, 43, 44, 87. Item 43 would have passed a visual test for solderability. Many items failing visual test produced no poor wetting defect.

Some or all of remaining poor wetting on tinned leads may have been due to not timming close enough to component body.

The kit of parts for 110 boards was split into two half-kits. In addition to the 53 stand-up capacitors per board, another 138 components per board in one half-kit were pretinned. In the other half-kit only the stand-up capacitors were pretinned. Thus in addition to the 5,830 stand-up capacitors normally tinned, for this experiment an additional 7,590 parts were pretinned. Fifty-four hours were charged to do this, or about one hour per board extra.

The leads were examined after tinning using a large illuminated magnifying glass to determine solder coverage. The results are summarized in Table I under Tinning. For most item numbers, good coverage was seen on every lead examined, and after about two dozen samples of an item were examined and found to be good, that item was accepted. About 25 percent of the components were rejected because cases of poor wetting were observed. Parts with the same item number were not necessarily identical - often there was more than one date code, and sometimes more than one manufacturer. In one case, one date code was rejected and another date code accepted. In other cases differences in solder coverage were seen for otherwise identical parts. The rejected parts were retinned by the same method as for the initial pretinning. For most cases, good solder coverage was seen after this second dip. Two items, numbers 67 and 87, had to be retinned in a more active flux (SRA) to obtain good coverage.

Assembly

Fourteen- and sixteen-pin DIP's were automatically inserted and the leads cut and clinched. The remainder of the parts were inserted by hand and the leads cut by hand. Large DIP's have their leads clinched; the remainder have one to four leads tack soldered to provide hold-down until the assembly is wave soldered. Whenever possible tack soldering is done on the component side to avoid having to flip the board. For 12 of the 203 components, tack soldering must be done on the solder side because of package configuration. Fifty-five boards were assembled with tinned DIP's and stand-up capacitors and all other parts untinned; the other 55 were assembled with all parts tinned except DIP's and those few parts which were not tinned at all.

Since pretinning increases the amount of solder on the leads and thus enlarges them, it was thought that there might be an increase in the number of cases of bent leads for DIP's not properly inserted. For the untinned half-lot, there were 5 cases; for the tinned, 8. This is not a significant difference.

Wave Soldering

About ten assembled boards were soldered per day on an Electrovert "Lambda Wave" soldering machine, using RMA flux applied as a foam, and eutectic solder at 500°F. The boards were loaded with the connector edge leading onto the finger conveyor which was run at 2 1/2 feet per minute. The connector and heat sink extensions were taped to protect them from the solder. No fixturing was used. Cleaning was in a methylchloroform vapor defluxer.

Evaluation

After soldering, PWA's at most manufacturers go to the touch-up operation; at our plant the wave soldering process is monitored by using evaluators to look for and record defects on the boards before they are touched up. These evaluators are manufacturing personnel, typically touch-up operators, who find, mark with an orange dot, record, but do not touch up, defects.

Engineering Evaluation

Because of the importance of the experiment it was deemed essential to use engineers from Manufacturing and Quality who could consider defects in more detail than could operators, and attempt to relate each defect to its cause - whether process or solderability - and who could also look at the overall system of producing PWA's.

Forty-one of the boards with tinned DIP's and stand-up capacitors, and forty of the boards with parts tinned except DIP's, were evaluated by engineers and the defects recorded by type and part number. The types of solder defect are given in Table II, along with which side of the board they are seen on and whether they are caused by poor solderability or by process problems.

TABLE II

Summary of Defect Rates by Defect Type

Cause Defect Type	Applicable Side of PWA	Applicable No. of Joints on 81 boards	Number Defects	Number Boards With This Defect	Defect Rate %	Defect Rate ppm	% of Boards With This Defect	Average Defects Per Board
S,P Insufficient Flow Thru PTH	comp.	92502[a,b]	426	77	0.46	4600	95	5.2
P Excess Solder	solder	107973[a]	254[e]	56[e]	0.24	2400	69	3.1
P Excess Solder	comp.	92502[a,b]	0	0	0	0	0	0
P Bridging	solder	105219	107	66	0.10	1000	81	1.3
P Exposed Copper -lead ends Attrib. to Insufficient	solder	20250[c]	15	13	0.074	740	16	0.19
P Insuff. Flow Fluxing	comp.	92502[a,b]	153	19	0.16	1600	23	1.9
P No Solder	solder	107973[a]	158	22	0.15	1500	27	2.0
P Solder Balls	both	d	-	12	-	-	15	-
P Tidal Wave	comp.	d	-	0	-	-	0	-
P Dull-Disturbed Joints	both	d	-	0	-	-	0	-
S,P Via Pin Holes	both	5508	18	7	0.33	3300	8.6	0.22
S Poor Wetting-Pads	both	215946	0	0	0	0	0	0
S Poor Wetting/Pin Holes Untinned Leads	both	105666	108	28	0.102	1020	38	2.6[f]
S Poor Wetting Pin Holes Tinned Leads	both	104972	29	20	0.027	270	25	0.72[f]
TOTALS	both	215966[d]	1267	81	0.59	5900	100	15.6

a) Includes 24 vias.

b) Excludes 115 inspectable joints tack soldered on component side and 16 uninspectable joints

c) Only copper-leaded components counted.

d) Applies to board as a whole.

e) Number uncertain as interpretation varied with evaluator.

f) Based on defect rate per lead % 1299 leads per board.

S Caused by poor solderability.

P Caused by process problems.

S,P Can be caused by both poor solderability and process problems.

III. FINDINGS

Evaluation

During the course of evaluating the boards the authors made a number of findings about the evaluation process itself. We discuss these findings because we believe that they apply not just to our plant but to the industry as a whole.

1. There is no one specification to which an evaluator can refer for a clear description of all the requirements and the factors which determine whether a non-ideal joint is to be rejected. The military has been working on this problem for several years and is aiming to issue a Document No. DoD-STD-2000-3, Acceptance Criteria for High Quality/High Reliability Soldering Technology. At present, defects are covered in MIL-STD-454 Requirement 5, and elsewhere.

   One category of defect is quite ambiguous. The military spec covering assembly of components on multi-layer boards allows the length of the lead to be so short that it does not project from the hole. The soldering spec, however, requires that the end of the lead be visible after soldering. Of course, a lead flush with the board will not be visible after soldering; should it be reported as "lead too short" or "excess solder"? A solution would be to require the lead to project at least, say, 0.020 inches, and a draft version of DoD-STD-2000-1 does this.

2. Each of the 81 boards examined by the engineers was first evaluated by one of four evaluators. The number of orange dots (reported solder defects) varied by more than a factor of five on comparable boards between these evaluators, and even the smallest number of orange dots was larger than the number of defects found by the engineers. This situation may be due in part to evaluator nervousness in knowing that their work was going to scrutinized.

3. It was confirmed that non-ideal joints can take far longer to evaluate than ideal ones. The principal reason for this is that a non-ideal joint, being small and shiny, requires careful examination, usually from more than one direction, to establish first, what it looks like, second, what category it belongs to, and third, whether it is really bad enough according to the established criteria to warrant rejection. This difficulty exists for all the types of defect except bridging, solder balls, no solder and tidal wave (solder ran over the top of the board during wave soldering).

   For example, for poor wetting of leads it is necessary to examine the angle the solder fillet makes around the entire periphery of the lead. If the fillet angle is uniformly small, the joint can be accepted at a glance; if it is large and varying it must be examined carefully, and this is true whether the joint does or does not then get rejected. The

significance of "defect" versus "non-ideal" may be thought of like this: reducing the defect rate reduces the amount of touch-up required; reducing the rate of non-ideal joints reduces the amount of inspection time required. Of course, reducing one reduces the other as well.

4. Some problems were associated with board design. For this particular board, the component side of solder joints of over 40 of the 203 components were difficult or impossible to inspect for adequate solder flow because of package configuration. On many stand-up capacitors, plastic spacers obscured the joints; for round and rectangular cans, the heat sink and nearby components were in the line of sight.

Solder Defect by Type

Poor wetting defects are reported by item number in Table I and summarized by part type in Table III. The defects for each board inspected are reported by defect in Table II and summarized in Table IV. The usual way of reporting solder defects is to add up the number of each kind of defect found and divide by the number of joints on the board (2 joints for every hole) to give a rate. In this report, a rate is calculated for each type of defect by dividing the number of that type found, by the applicable number of joints for that defect (for 81 boards). The applicable number for each type is discussed in the following pages. The defect rate is given in percent and parts per million; also reported are the percentage of boards showing each defect and the average number of defects of each type per board. Recommendations for greatly reducing the reported defect rate are given in Section IV.

As discussed above, a meaningful experiment and meaningful process control require good data. For PWA defect rate reporting, there has been a lack of precision in the definition of the various defects and a lack of understanding of their causes. The discussion that follows is aimed at providing a comprehensive list of solder defects and principal causes.

1. Insufficient flow through plated-through holes. This defect has conventionally been called "insufficient solder". As such it is too easily confused with poor wetting. With the longer title, it is meant to apply only to joints on the component side where the solder did not rise in the hole far enough to flow out onto the pad. This situation could be caused by the hole being blocked or by insufficient time at temperature (conveyor too fast, solder not hot enough, etc.). Since poor solderability implies long wetting time, it too can be a contributing factor, but no case of this defect attributable to poor solderability was observed.

   In this experiment, insufficient flow not attributable to insufficient fluxing of the board was seen on only 8 of the 203 components - the round and rectangular cans - and only on certain leads then. These components have gold-plated Kovar leads that extend from the bottom of the package. For the rectangular cans, insufficient flow was seen only on the 4 corner leads (numbers 1, 12, 13, and 24). Insufficient flow was never observed for the hybrid packages with gold-plated Kovar leads extending from the side. This situation was very puzzling.

TABLE III POOR WETTING BY PART TYPE

Type of Part	Number of Parts Per PWA	Number of Parts 81 PWAs	Number of Cases of Poor Wetting Per 100 Parts Untinned	Number of Cases of Poor Wetting Per 100 Parts Tinned
Stand-up capacitor	53	4293	N/A	0.37
Axial capacitor	23	1863	3.0	0.87
Resistor	43	3483	0.057	0
DIP	46	3726	2.9	0.16
Rectangular Can	3	243	0	1.7
Round Can	5	405	0	0
Side-lead Hybrid	3	243	0.81	0
Power Transistor	2	162	21.7	0
Axial Diode	9	729	0.27	0
Other	16	1296	0.088	N/A
	203	16443		

TABLE IV MAJOR DEFECTS BY TYPE AND CAUSE

Type of Defect	Defect Rate %	Per Joint ppm	% of Boards With This Defect	Average Defects Per Board
Process-related (total)	0.52	5200	100	13.7
-Insufficient flow	0.46	4600	95	5.2
-Excess solder	0.24	2400	69	3.1
-Bridging	0.10	1000	81	1.3
-Insufficient flux or no solder	0.31	3100	52	4.0
Solderability-related				
-Untinned leads	0.102	1020	38	2.6
-Tinned leads	0.027	270	25	0.72
-Via pin holes	0.33	3300	8.6	0.22
Orange-dotted non-defects				more than 10

The solution was provided by an inspector who observed that it is the corner leads which are tack soldered. Further understanding of the mechanism came from a realization that these 8 components are, because of their configuration, tack soldered on the solder side of the board. The solder joint prevents flux from getting into the barrel of the hole during wave soldering. Without flux, the solder doesn't flow. To confirm that tack soldering was the cause, different leads were tack soldered on five boards; the cases of insufficient flow on those boards were seen on the leads which had been tack soldered.

Only 4 other components are tack soldered on the solder side. These are the power transistors and the variable capacitors. The power transistors, although held in place by screws, are hand soldered because the bottom of the package is flush to the board and inhibits air escape during wave soldering. The variable capacitors have one lead on the main axis of the component; this lead is not accessible on the component side. These 4 components are not inspectable for insufficient flow on the component side and neither are some 31 stand-up capacitors with plastic spacers.

Stand-up capacitors are tack soldered on the component side by a deft maneuver of holding the component above the board with the leads extending through the holes, applying heat and solder to one joint and promptly pushing the component down into position after the solder flows. All two-leaded components have one lead tack soldered in place on the component side of the board; these joints are not subject to the defect category of insufficient flow.

As shown in Table II, 426 cases of insufficient flow were found. At least one case was found on nearly every board. The applicable number of joints is the number of inspectable joints on the solder side of the board, less those that were tack soldered on the component side. This gives a defect rate of 0.46% or 4600 defects per million applicable joints. Another way of reporting the defect rate is to say that an average of 5.2 cases of insufficient flow was seen per board.

The actual rate may have been somewhat higher. The package configuration that prevented tack soldering from the component side also made inspection difficult. For the rectangular cans, two package styles were seen for the same part number. One style had a flange at the bottom which extended out over the heat sink, giving a clearance of only about 0.01 inches and precluding any possibility of inspection.

2. Insufficient fill of vias - either side. If a via fills as the board crosses the wave but loses some of the solder as it exits, there will be a depression in it. The spec allows the depth of the depression to be 25% of the board thickness. This defect has, as has the previous one, been

referred to as "insufficient solder." Its cause is entirely separate, and it differs in appearance, in that the solder surface is smooth and concave. Insufficient fill is seen on boards soldered on oil-mix machines, because the oil reduces the surface tension of the solder, making it easier for the solder to flow into, and also back out of, the holes. Oil was not mixed with the solder in this experiment, and no case of sufficient fill was seen.

3. Excess solder - solder side. The Westinghouse spec required that solder not project beyond the end of the lead. This is appropriate to exclude icicles, but the case of semi-clinched leads was not covered. Solder frequently extends beyond the maximum extension of semi-clinched leads after wave soldering, even though it does not exceed the height requirement of 0.060 inches. Because of differing interpretations of the definition of this defect between the engineering evaluators, the data are somewhat inexact, but most boards had defects of this type. The rate reported in Table II is 3.1 per board; it was seen as high as 33. Most of the joints orange-dotted by the evaluators appear to be cited for this defect. It has now been virtually eliminated by making the appropriate changes in the Westinghouse specification (see Section IV).

4. Excess solder - component side. This defect occurs when a hole is too large and the board runs too deep through the solder wave. In extreme cases, solder has flowed up and out onto the board and spread to nearby components. No cases of this defect were found in the experiment.

5. Bridging. Bridging is a special case of excess solder. It is usually easy to detect. It is totally unacceptable because it is a short circuit between leads that are not intended to be connected. There were a total of 107 bridges for an average of only 1.3 per board, but 81% of the boards had at least one bridge.

6. Exposed copper - lead ends. Automatically inserted components have excess lead lengths cut off automatically. Manually inserted components are tack soldered and the leads are then cut to a length of 0.040 inches with a special hand tool. The lead cutting, whether automatic or manual, exposes the unplated base metal. In practical terms, it is only exposed copper lead ends, because of the difference in color from the solder, which are detectable. Recent military specifications require conformal coating of PWAs, and this defect is no longer grounds for rejection.

   In the experiment, each observed case of "exposed copper - lead ends" was at a corner of the leading edge of the board. It was attributed to a failure of the flux foam to cover this spot as the board passed over it. Points behind the corner may also have not been fluxed adequately but once the board had entered the solder wave, flux flowed to these areas in time for adequate soldering to occur. The applicable member of joints for this defect is the number of copper leads.

7. Insufficient flow - fluxer. A more serious failure of the fluxer exhibited itself in a highly localized problem of insufficient flow on the leads of many adjacent components. The defect rate for this defect and the preceding one is small, but on a per-board basis, 37% of the boards showed evidence of improper fluxing.

8. No solder. This defect is very easy to detect, for there is no joint. It is caused by some part of the board failing to come into contact with the solder wave. This defect was seen on 27% of the boards.

9. Solder balls. Loosely attached solder balls are a threat to reliability as they may become dislodged and cause a short. Since solder balls may be found anywhere on a board, not necessarily a joint, there is no applicable number of joints for this defect. One or more solder balls were seen on 15% of the boards. Occasionally a joint on the solder side may have a spherical fillet instead of the normal concave shape. The cause of this "ball" appears to be volatile materials within the plated-through hole pushing the solder outward. The solder freezes before the gas can escape.

10. Tidal wave. The setting of wave height is critical on the wave soldering machine. A typical board is only 0.060 inches thick. If the wave isn't high enough, it will miss the board; too high, and it flows over the top to produce a tidal wave. One complicating factor is that the board motion through the wave can cause the solder to pile up in front of the leading edge. Another is that the board may bow as it expands from heating. No cases of tidal wave occurred in this experiment.

11. Dull or disturbed joints. Dull solder joints are produced on the board as a whole if the composition becomes deficient in tin (tin oxidizes to form dross faster than lead), or becomes contaminated with other metals (e.g., copper or gold), or with dross particles.

    Disturbed (non-smooth) joints are produced if the joint is disturbed as the solder is freezing, say by touching a component or jarring the board as it exits the solder wave. The solder composition is checked frequently, eutectic solder freezes quickly, and boards are not likely to be disturbed, so in practice these defects are not seen.

12. Via pin holes. Pin holes are tiny depressions in an otherwise smooth solder surface. The requirement is that if the bottom of the hole cannot be seen, the joint is to be rejected. Several years ago in an effort to aid in the inspection of such holes, the otoscope (a medical instrument for examining eyes and ears) was introduced into the factory. The otoscope projects a beam of light very nearly parallel to the line of sight and thus is best able to light the bottom of a hole. The magnification lens on the otoscope also helps the evaluator look for something which is necessarily difficult to see.

    The rationale for the criterion is that if the bottom can be seen, the hole is probably due to solder shrinkage during solidification; if not, it may be due to poor wetting and may be a threat to reliability. In the

case of a via, there is no lead and the implication is poor wetting of the plated-through hole. The rate per via (each via counted twice) was 0.33%, but since there were few vias, the rate per board was only 0.22).

A large hole in a joint is assumed to be caused by volatilization during solder freezing of entrapped flux, or by water vapor or air escaping from a hole in the through-hole plating. If oil is used with soldering, holes sometimes occur if too much oil is mixed with the solder. No large holes in vias were seen.

13. Poor wetting - pads. Poor pad wetting is exhibited by the fillet making a large angle with the pad, or by non-uniform coverage of the pad, or in extreme cases, as exposed copper of the pad. No cases were seen.

14. Poor wetting or holes - leads. The overall comparison of solder defect rates for tinned and untinned leads is given in Table II; cases of poor wetting are reported by item number in Table I and by part type in Table III. The defect rate for poor lead wetting is given in Table II on a per-joint basis as 1020 and 270 parts per million for untinned and tinned leads respectively. In Table I the rates are given per lead.

Poor wetting of a lead means that the angle the solder fillet makes with the lead exceeds 90° somewhere on the lead periphery. The presence of a pin hole or void was also taken as an indication of poor lead wetting, although these defects could have other causes. Not reported were the many cases of "non-ideal" wetting in which the fillet was not bad enough to cause rejection but still bad enough to require careful examination. The number of such joints may exceed the number of rejected joints by a factor of three to ten.

The rate of poor lead wetting depends, of course, on the solderability of the components being soldered. For this batch of PWA's, the rate was quite low.

Of the 75 different items that were soldered (not counting the 11 stand-up capacitor items, all of which were pretinned), it is remarkable that only 4 showed significant wetting problems without tinning. One item, number 67, which required highly active flux to give good coverage, did not have a significant rate of poor wetting after wave soldering without tinning, for reasons that are not known. The remaining 70 may be assumed to have had adequate solderability at the time they were wave soldered. The four problem parts (item numbers 39, 43, 44 and 37) showed far fewer wetting defects when tinned. The stand-up capacitors all had pretinning because they had long been recognized as having unacceptably high rates of poor wetting when soldered without it.

The 29 cases of poor wetting of pretinned parts require careful consideration. For these cases, inadequate fluxing has been eliminated as a possible cause, so it must be concluded that in spite of pretinning and inspection, they did not (by definition) have the necessary level of solderability. There are four possible causes for this situation:

a) The parts were solderable when tinned but lost their solderability before they were soldered, from oxidation or contamination or abrasion. Oxidation is not a likely cause because properly solder-dipped component leads are known to remain solderable for years.

b) The leads had good solderability where they were examined but not where the joint formed. This is a possible explanation for at least some of those cases where the poor wetting was seen on the component side but not on the solder side (81% of the total).

c) The parts were not examined. This is a possibility; if each of 2 dozen or so components for a given item number were seen to have good solder coverage after tinning, it was assumed that the remainder also had good solder coverage and they were not examined.

d) Examination for solder coverage after tinning is not an adequate means of predicting good wetting after wave soldering. This possibility seems self-contradictory, in that in both cases examination for wetting is the basis of the decision. In fact, many untinned parts, known from pretinning and examining of similar ones to have less than ideal solderability, never showed poor wetting after wave soldering. It is possible, however, for de-wetting of a pretinned lead to occur after it is re-exposed to molten solder during wave soldering.

It is worth noting that one part which appeared to have good solderability as received showed a serious wetting problem when not tinned, as shown in Table I. Item number 43 showed adequate solder coverage when tinned, but had a high defect rate (9 cases out of 82 untinned leads). These leads are supposed to be hand soldered before wave soldering, because the component body blocks the top of the hole, creating an air trap during wave soldering. The operators are instructed to tack solder, so they make no attempt to get a good joint.

It is possible to calculate a predicted number of wetting defects for a hypothetical board populated entirely with tinned or untinned parts, as follows. There are 1,299 leads per board. From Table I, the rate of poor wetting per lead is 0.20% and 0.055% for untinned and tinned leads. Multiplying the rate of poor wetting per lead by the number of leads per board gives a predicted rate of poor wetting per board. The results, 2.6 and 0.72, appear in Table II. An average of fewer than one defect per board implies that many boards will be without defect.

General Findings

1. Leads of some automatically inserted DIP's showed vertical scratches above the fillet, occasionally deep enough to expose bare metal (Kovar). In a few cases, the metal removed was present as a peeling, which could possibly come off later and cause a short circuit, although the use of conformal coating should make this unlikely. Nevertheless, it seems desirable to try to prevent the scratching.

2. The effects of uninspectability have already been mentioned. This is just one example of how board design affects producibility. Here are some others: The metal heat sink appears to be designed to cover as much of the board as possible. However, the leads of some properly inserted axial components come very close to the heat sink. A minor shift of these components during wave soldering can result in the need to resolder and reposition them during touch-up. As another example, it was soon noted that certain areas of the solder side of the board tended to accumulate excess solder; the excess had to be removed during touch-up.

   Finally, when the pad on the solder side of the board has no lead visible, the only way an evaluator can determine if the hole is a via or a joint with insufficient lead extension is to flip the board and find the same hole on the component side. This problem could be prevented by the use, on the solder side, of a special pad shape for vias. If the special shape were also used on the component side, it would aid in inspecting for missing components. At our plant, new board designs have vias readily identifiable by their smaller hole (0.018 inch) and pad (0.055 inch) diameters. An additional benefit of smaller vias is that they are less vulnerable to defect no. 2, insufficient fill.

IV. DISCUSSION AND RECOMMENDATIONS

Evaluation

There should be an improved document that can be used by evaluators which shows and describes clearly every kind of defect that is ever found on any PWA. The criteria for each defect should be clearly traceable to the applicable military requirement.

In particular, "excess solder - solder side" should be redefined as "the solder exceeds the height requirement, or it is on the board, or it is likely to break off, or it forms a convex fillet that extends beyond the pad, or the lead is not visible". This redefinition is consistent with applicable military specifications and if adopted would virtually eliminate instances of this defect.

We believe that one of the most important yet often overlooked ways to reduce the solder defect rate is to evaluate PWA's immediately after wave soldering, and to do a good job at it. The evaluators should be trained and retrained. Training materials should include pictures, an audio/visual program, and actual PWA's with known defective joints that can be used for practice and self-testing. Special emphasis should be made on the distinction between a non-ideal joint and a defective joint, in order to get the willing cooperation of every evaluator in reporting only genuine defects.

This experiments suggests the importance of training evaluators to look for causes or at least trends. For example, exposed copper was reported many times for capacitor number 61, which is on a corner of the board, but never for numbers 31 and 32, yet all are item number 38. If, as was done in this

experiment, part numbers were reported at least for certain defect types, then these trends would quickly become obvious and problem solving would be accelerated. Parts showing a pattern of poor wetting should be reported to Incoming Inspection.

The way to evaluate the wave solder operation is to evaluate wave-soldered PWA's; the way to evaluate the evaluation operation is to audit it. Such an audit was provided by this experiment and the results indicated that far too many joints were being marked for touch-up. Touch-up takes time and costs money. Worse, the real defect rate is obscured by the erroneous reporting of non-defects, so no corrective action can be taken. Without accurate defect reporting, there can be no realistic and meaningful definition of board yield after wave soldering.

Process-related Defects

The great majority of the observed defects are of this type and we believe that most of these defects could be eliminated fairly easily.

1. "Insufficient flow through plated-through holes" has now been virtually eliminated by requiring that any solder-side tacking be done by producing a complete fillet on the component side of the board. (This assumes the lead is visible there.)

2. The wave solder operator should be instructed to look for cases of no solder and immediately resolder any boards he finds with this defect.

3. Loosely adhering solder balls, if created during wave soldering, could be driven off the board with the high-pressure sprays of an in-line defluxer. Any remaining solder balls would be further immobilized by conformal coating and thus should be acceptable.

4. Reducing the number of via pin holes would not be as easy as the above changes, but it does not seem impossible either. One possible way would be to measure the solderability of the plated through holes, rather than just evaluate the appearance of coupons after wave soldering. If found to be marginal, the boards could be hot-air leveled.

5. Bridging and those cases of excess solder that remain after changing the definition can best be prevented, if it is decided that it is worth while to do so, by use of a hot air knife.

With excess solder eliminated (by changing the spec), and the above process-related defects except bridging eliminated (by changing the process), the predicted defect rate would be less than four defects per board; eliminating bridges would reduce the rate to two and one-half per board even without doing anything about poor wetting. At such low defect rates, defect-free boards would be a common occurence. Reducing the rate of process-related defects will be helped by using the increased information made available from improved evaluation.

Solderability Management

Is it worth while to do anything about part solderability? With the defect rate observed on this particular batch of PWA's, the answer appears to be no. However, the wetting defect rate on other batches may run much higher than for this one. In any case, once the spec and process changes suggested in the previous section are made, then the effect of improved solderability will become seen, and solderability management will become worth the time required. The method we recommend is solderability testing rather than pretinning, as discussed below.

The rate of poor lead wetting was reduced by a factor of more than three, and on a per-joint basis was less than 300 ppm. Had a board with more serious parts solderability problems been selected, the reduction factor would presumably have been much greater. Also, with the experience gained in solderability enhancement for this experiment, it seems likely that further reductions in this defect rate could be achieved, particularly if a solderability tester had been used instead of the method of pretinning plus inspection for solder coverage.

It needs to be emphasized that pretinning alone is not the same thing as ensuring good solderability. Components must be examined afterwards for good solder coverage and the examination must be thorough. In our experiment, this approach turned out to be neither necessary nor sufficient. On the one hand, nearly all of the parts not now pretinned had adequate solderability anyway. On the other hand, of the four item numbers showing a significant incidence of poor wetting, only one was given adequate solderability with single dip tinning, and one would not have been adequately tinned with a double dip using RMA flux. It is known that even highly active flux cannot give good tinning on some problem component leads, and 29 cases slipped by our best efforts to deliver only highly solderable parts to be inserted.

We can only speculate on the results that would have been obtained if a solderability tester had been used instead of universal pretinning and inspection, but it is worth noting that solderability testing would detect a tendency to de-wet, and could be set up to always check for solderability on that part of the lead that actually forms the solder joint. A tester would presumably have noted that most of the item numbers did not require pretinning, and may have predicted a potential problem of via pin holes. A solderability tester gives quantitative data upon which to base a decision of whether pretinning is required. Solderability testing is also known to be able to predict shelf life, so that accepted parts would still be good when needed.

A factor worth considering in the comparison of pretin-plus-inspect versus solderability testing is the effect that each option has on the parts suppliers. If a supplier knows that the parts he sends in will be pretinned anyway, he will have no incentive to deliver solderable parts. In fact, one reason for the deteriorating level of parts solderability over the past few years is the increasing use by PWA manufacturers of highly active flux for

wave soldering. (This option of course is not open to manufacturers of military hardware.) On the other hand, if the supplier knows that the parts he sends in will be tested for solderability, he will have the necessary incentive to deliver solderable parts. Our Incoming Inspection records show a dramatic drop in the rejection of parts tested for electrical malfunction and for damaged packages after inspection for these defects was initiated.

Once the process changes discussed above have been made, our experiment could be repeated, this time testing for solderability, pretinning only as needed, and reporting cases of non-ideal as well as poor wetting. It would be the goal of that experiment to produce defect-free PWA's and achieve a defect rate below 50 ppm. If such a reduction could be made, then it should be possible to eliminate 100% inspection, and the time saved here should more than offset the time required for solderability management.

Solderability Management Cost Comparisons

In this section we present an analysis of the options available for reducing PWA defects. The options are shown in Table V and discussed below. The question to be answered is whether the number of operators needed to run a program of solderability management can be offset by a reduction in the number of operators needed for evaluation and touch-up. The pretinning of stand-up capacitors is assumed to continue as-is for all options, so the requirements for this operation are excluded from the calculations.

TABLE V
PWA SOLDERABILITY MANAGEMENT OPTIONS

No.	Method	Time for Eval. and Touch-up Minutes per PWA	Time for Solderability Management Minutes per PWA	Option total Minutes per PWA
0	Present Method	30	0	30
1	Improved specs, training, and process	10	0	10
2	Option 1+ Solderability Management A			
	Machine pretin every part		5	
	Sample inspect for solder coverage		2.5	
	Total	1	7.5	8.5
3	Option 1+ Solderability Management B			
	Solderability test ever lot		10	
	Pretin or return failed lots		1.5	
	Total	0.5	11.5	12
4	Option 1+ Solderability Management C			
	Solderability test selected lots		2	
	Pretin or return failed lots+ pretin suspect lots		1.5	
	Total	0.5	3.5	4

0. Present Method. It is difficult to get accurate figures for the time to evaluate and touch up, but we estimate a total of at least a half hour per average PWA.

1. Improved Specs, Training, and Process. We have already noted that most of the current PWA's solder defects could be eliminated without a solderability management program by making straightforward improvements in the specifications, the evaluator training, and the wave solder process. If this is done, then we predict that the reported defect rate will drop to around 3 defects (all cases of poor wetting) for a board of the size used in our experiment or about 1 per average board. The time required for evaluating and touch-up would then be reduced, but not proportionately to the reduction in the number of defects. Without solderability management, 100% evaluation would still be necessary. There are no data we know of that would allow a calculation of how much time would be saved by option 1, but we will estimate that it is a factor of two thirds, so that the operator time for this option would be 10 minutes per board instead of 30.

2. Solderability Management A, Tinning Plus Inspection. A machine to automatically tin all of the various kinds of components does not now exist. For the volumes characteristic of manufacturers of PWAs for the military, we assume that the most practical solution would be several different semi-automatic machines (say 4) which would require part-time attendance of an operator and maintenance person. At our plant the number of PWAs produced is four times the number of component lots received. For the calculations that follow, we assume that this ratio stays constant over a range of production volume. We estimate 20 minutes and 10 minutes per lot to pretin and to inspect for solder coverage. This equates to 5 and 2.5 minutes per PWA.

3. Solderability Management B, Every-Lot Solderability Testing. We assume that solderability testing will be done on an average of 25 pieces per lot, at a minute apiece, and we allow another 15 minutes for handling and record keeping. This equates to 10 minutes per PWA. Based on the results of our experiment we predict that most lots would pass the solderability test, so that the additional time required for pretinning or returning failed lots would be small. We estimate a failure rate of 10%. Using the above estimates of 5 minutes per PWA to pretin all components, this would mean 0.5 minutes to pretin 10 percent of them and another 1 minute to retest for solderability.

4. Solderability Management C, Selected-Lot Solderability Testing. One of the results of this experiment is that while some types of component showed high rates of poor wetting (see Table III), other types of component had a very high probability of good solderability, including the high-volume components, resistors and DIP's. Also, we assume that the pretinning of stand-up capacitors can be improved so that these parts

always have good solderability. It should be possible to eliminate many types of components from testing and do only those parts known from experience to be problems. If evaluators reported back to Incoming Inspection which parts were showing poor wetting, these parts could be targeted and the situation resolved before assembly. A further reduction in the time for solderability testing would be made possible by automating the parts handling. With the combination of judicious sampling and automation, we believe that the number of people required could be reduced by 80%. (The time required for handling failed lots would remain the same.) If such a reduction can be achieved, then this option is the best.

The inspection times shown for options 2, 3, and 4 are based on the assumption that the defect rate is consistently so low that the 100% inspection requirement can be waived, and only sample inspection is done.

V. SUMMARY

This experiment set out to show that improved solderability could reduce the rate of solder defects on PWA's. The test board was chosen because of the wide mix of parts on it. The solder defect rate for this board was found to be 0.59% on a per-joint basis or 15.6 joints per board.

It was found that most of the solder defects were process-related, but that most of these defects could be eliminated by changing the definition of excess solder, by changing the instructions for solder-side tack soldering, and by ensuring that the wave solder machine is always adjusted so that every board is fully contacted by flux and solder. Loosely adhering solder balls, a minor problem, could be removed by a high-pressure solvent spray during defluxing. Bridging, although common, is also a minor problem because it does not require significant time to find or correct. If deemed worthwhile, it could be eliminated by a hot air knife.

With these defects dealt with, the remaining rate would be due to poor wetting. The via pin holes were presumably due to insufficient solderability of the through-hole plating. Testing the solderability of the holes might have predicted a problem here but we have no data. Without pretinning, the rate of poor lead wetting was 0.102% or 1020 defects per million joints, 2.6 defects per board. With pretinning and inspection, the rate was 270 per million, better than a factor of three smaller. This corresponds to a rate of 0.7 defects per board.

With the experience gained in solderability enhancement from this experiment we believe that further reductions in the defect rate are possible. If achieved consistently, it should be possible to eliminate 100% evaluation, as defect-free boards would be the norm. The time saved here could then justify the time required for solderability management.

Inspection for solder coverage is a necessary part of pretinning as a means of assuring good solderability. A preferred means, but one which could not be used for this experiment because of its unavailability, was a solderability

tester. We calculate that the time required for solderability testing is substantially less than the time for evaluation and touch-up.

The defect rate found by the engineering evaluators was substantially less than that found by the manufacturing evaluators. The discrepancy is attributed to the lack of a single comprehensive document clearly describing each defect type, to insufficient training, retraining, and self testing, and to the lack of auditing. Excessive defect-finding means excessive touch-up costs and reduced utility of the data in trouble shooting.

Some design changes are recommended, including designing for inspectability (all leads on the component side visible,) use of a special pad shape or size to designate vias, and modifying the heat sink to make axial-leaded components less vulnerable to shorting.

VI. ACKNOWLEDGMENTS

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PRINTED WIRING BOARD SOLDERABILITY

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INTRODUCTION

Process Engineers fondly imagine that their skills have great impact on the yield and throughput of the flow soldering equipment in their care. In fact, the battle is largely won or lost long before the Process Engineer has an opportunity to enter the fray. Given excellent PWB design and quality, and perfectly solderable components, the Process Engineer would be considered of little value to the manufacturing manager and might be in danger of becoming extinct or simply dying of boredom. Given unsolderable PWBs and components, the Process Engineer still has little effect on the results of the flow soldering process.

It is in the area of acceptable, but not optimal solderable PWBs and components that the Process Engineer can have great impact. Once the parts have reached the assembly line, his tools are weak indeed, but every Process Engineer has, at some time, managed to get very poor assemblies to solder acceptably and to solve solderability problems in spite of the constraints imposed on the use of such powerful tools as "hot" fluxes.

This paper addresses the solderability of PWBs, and the tools and techniques by which TI assures that solderable PWBs will be delivered to assembly lines. The mechanisms are presented by which the other parts and materials that affect apparent PWB solderability are controlled, as are the effects of the applicable military specifications on purchased parts and material quality.

PRINTED WIRING BOARD SOLDERABILITY

The single component type most likely to challenge a Process Engineer is the PWB. A Multilayer Board (MLB) may have a value of over $2,500.00. Lead time to make a MLB is likely to be several months. A MLB assembly that must be rejected for an MLB flaw can easily have a value of over $10,000.00 and can easily cause far greater cost while severely impacting schedules. A marginal PWB must often be made to solder well.

In contrast, faulty electronic components that sneak through the incoming inspection net are simply replaced, and unsolderable component leads are quickly discovered and either tinned or replaced. Bad solder is replaced, and faulty processes or equipment are corrected or replaced.

Printed wiring boards are addressed in this paper as seen by the process engineer or the Qualification and Evaluation Laboratory staff. Potential defects such as delamination, which are considered to be serious threats in the TI MLB shops, are almost nonexistent to the assembly Process Engineer since these defects are very effectively caught in the Board Shop and are seldom seen on the assembly line. The assembly Process Engineer uses bake cycles ranging from six hours to twenty-two hours to prevent delamination and gas evolution in the plated-through-hole (PTH) during flow soldering. He is primarily concerned with solder joint defects that cannot be prevented by baking and that may be made worse by baking. In the Equipment Group, the process engineer has several process labs and a Failure Analysis Lab to help diagnose solderability problems, but the most valuable tool is the inspection after flow soldering, and before touch-up, so the true flow soldering yield can be determined.

There are two serious PWB solderability problems that are inherent in the process of PWB manufacture and not simple escapes from inspection. These two are voids through the PTH barrel wall and exposed copper-tin intermetallic compounds instead of tin-lead on surfaces that are supposed to be solderable. In each case the basic flaw is almost impossible to avoid completely with current technology, and in each case Mil-P-55110D provides too little protection for the assembly shop.

BARREL WALL VOIDS

Voids through the PTH originate in the failure of the activation and electroless copper steps in the plating process. The properly performed activation and electroless copper plating process is very aggressive and can penetrate along glass fiber surfaces and even encapsulate unintended particles and contaminants on the drilled hole's surface. However, at times this process does fail to completely activate the surface and to establish the integrity of the barrel wall. When this occurs, a stream of bubbles evolved from the void between the barrel wall and the laminant prevents the electroplated copper from covering the unactivated area. The resulting void, which can sometimes be seen at this stage, is most often sealed with solder in the reflow process so it cannot be seen by visual inspection after reflow.

Holes through the barrel wall are considered to be inherent in the PWB manufacturing process and are acceptable by MIL-P-55110D. Figure 1, taken from MIL-P-55110D, shows the holes that are allowed through the barrel wall in any cross-section through a PTH. Three holes are allowed through any cross-section, and up to 10% of the barrel wall could be void of copper and still satisfy MIL-P-55110D.

Examples such as Figure 1 in MIL-P-55110D have led many PWB manufacturers to sincerely believe that voids in the barrel wall do not cause defects in solder joints if proper baking is performed, but few assembly Process Engineers agree. At one time it might have been necessary to accept holes through the barrel walls, but at Texas Instruments both PWB Engineers and assembly Process Engineers agree that less than 2% of PWB lots have barrel voiding. On the other hand, significant losses have occurred from single lots of PWBs when the problem was discovered after the whole lot had been flow soldered.

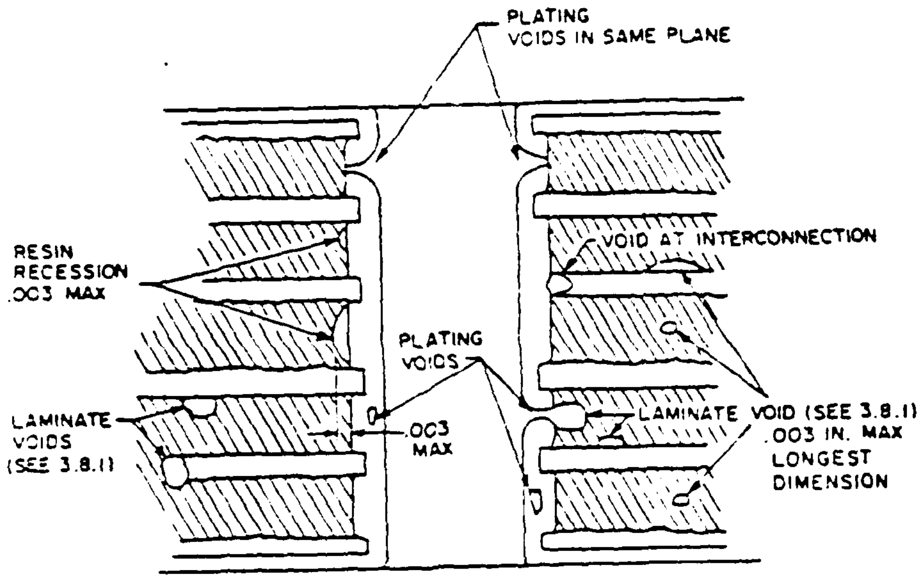

FIGURE 1

MIL-P-55110D PLATING VOID PRESENTATION

Barrel voiding is obviously becoming a smaller problem in terms of lots affected, while it is becoming a more expensive problem on those few lots that are affected. Recognizing that barrel voiding will occur in some cases, Texas Instruments has chosen to depend on a screening test in which one board from each lot is run across a wave soldering machine in one of the PWB shops under conditions similar to those found on the assembly lines. Flow soldering bare (unstuffed) PWBs is a rigorous test since solderable component leads help draw solder up through the PTH, and to some degree the leads disguise the effects of flaws in the barrel. The results of gas bubbling up through the solder plug and of bubble shrinkage as the solder freezes are obvious on the bare PWBs. Acceptance criteria are shown in Figure 2 from DOD-STD-2000-1. Barrel voiding is invariably a lot problem, so failure of this test results in scrapping of the lot by the PWB Shop. One purpose of this test is to catch the less than 2% of voided PWBs at the PWB Shop to allow immediate corrective action to the PWB fabrication process and to allow replacement of any PWB lot with voided barrels before they are put into the warehouse and finally disrupt the assembly process and schedule.

The assembly Process Engineer has only three potential techniques to overcome barrel voiding, but none of them are desirable. The voiding becomes worse with each pass over the solder wave so multiple passes over the solder wave don't help. Extensive baking greatly increases the thickness of the copper-tin intermetallic layer and depletes the tin on the knee of the plated-through-hole, thus reducing solderability. Extensive touch-up is costly and can result in creation of new defects. MIL-P-55110D should be modified to make voids through the barrel wall unacceptable.

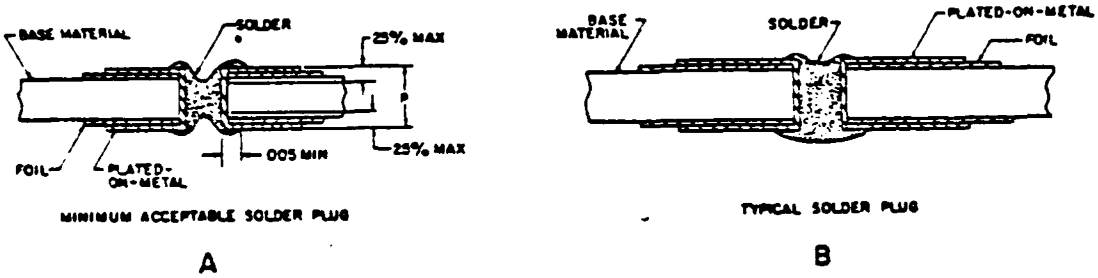

FIGURE 2: DOD-STD-2000-1 PLATED-THROUGH-HOLE SOLDERING CRITERIA

EXPOSED INTERMETALLIC COMPOUNDS

The second, and more serious, PWB solderability problem is that of a lack of solder on the pad-to-barrel knee. This lack of solder is disguised by the presence of the tin-copper intermetallic compound Cu_6Sn_5 which looks like dull solder. When the tin-lead plated PWB is reflowed to seal the tin-lead coating and verify the wettability of the copper substrate, the shape of the molten tin-lead will be determined by surface energy considerations. With perfectly wetted substrate and ample molten solder, the surface solder on the pad and on the inner surface of the barrel will meet the substrate surface at the knee tangentially as shown in Figure 3. It is not uncommon for there to be a narrow area at the knee where a metallographic cross-section would show no solder on the surface, but only Cu_6Sn_5 intermetallic compound resulting from the reaction of the tin in the solder and the underlying copper. Figure 4 shows the intermetallic layers and the slight exposed intermetallic layer at the knee. This narrow intermetallic exposure is not normally visible from the surface because the uppermost Cu_6Sn_5 intermetallic looks like dull solder and because surface diffusion constantly replenishes the tin on the surface of the intermetallic. It is this very thin tin surface layer that allows most reflowed PWBs to flow solder well.

There are two phenomena that can cause the molten solder to withdraw from the knee area during the reflow process. First, the angle at which the solder surface meets the PTH surface is determined by the relative surface energies of the materials. Solder on clean copper, with the help of a mild flux, assumes a wetting angle of almost 0^{o} as it spreads on the copper. The angle of wetting of molten solder on the tin-copper intermetallic compounds has been seen to vary from 0^{o} to 45^{o} on PWBs submitted to the Equipment Group Failure Analysis Lab for poor solderability.

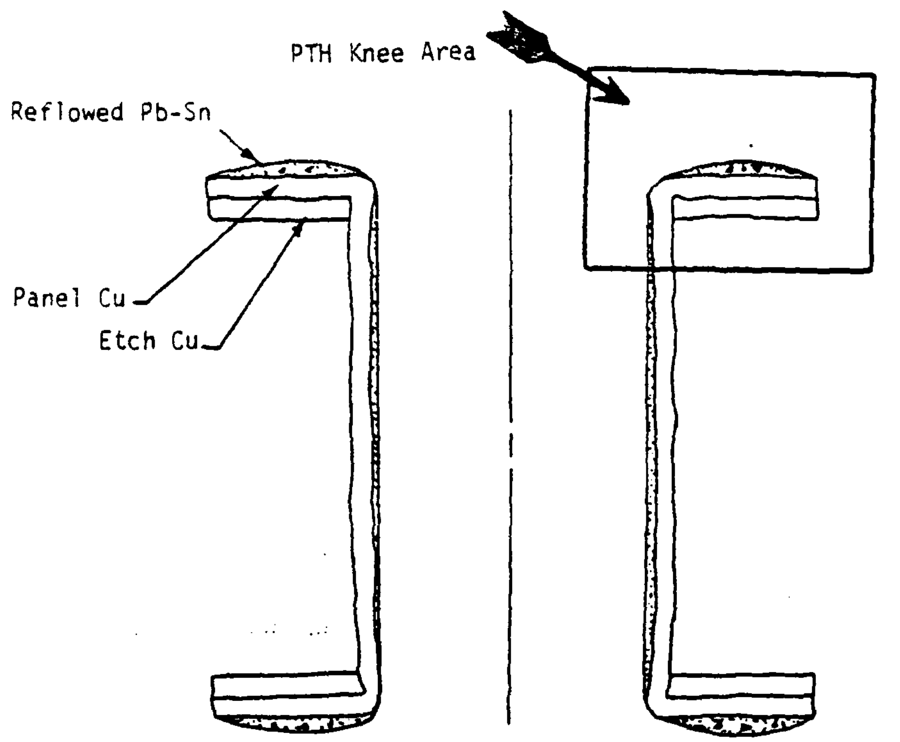

FIGURE 3: Cross-section of a PTH with perfect wetting and no intermetallic formation

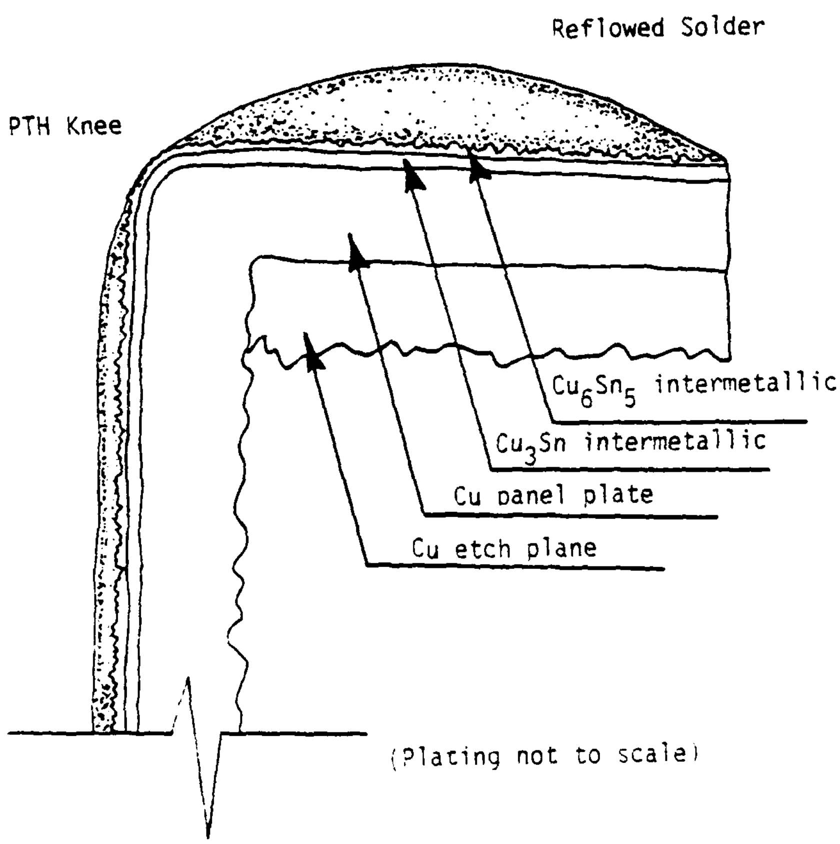

FIGURE 4: Cross-section of a normal reflowed PTH knee

This angle at which the solder surface meets the substrate will determine the area that a given volume of solder may cover as shown in Figure 5. Similarly, with the wetting angle constant, a smaller volume of solder will cover a smaller wetted area.

Thus, when the amount of tin-lead on a surface is too small or the substrate (intermetallic layer) becomes too difficult to wet sufficiently, the molten solder must withdraw from some of the surface on which it was plated. The result of this withdrawal, as shown in Figure 6, will be a bare area at the knee that is too wide for surface diffusion to be able to replenish the very thin surface layer of tin before it is consumed by reaction with copper diffusing up through the intermetallic layers. When this occurs, some of the copper atoms exposed at the surface oxidize and the exposed Cu_6Sn_5 layer becomes very difficult to wet with solder. At this point, only a very hot soldering iron or a very "hot" flux will tin the intermetallic surface. Hot fluxes are not allowed on military products, and the controlled temperature soldering irons being installed on many assembly lines may not always be able to touch-up PWBs having this problem.

In extreme cases, where extensive baking has been performed, the Cu_6Sn_5 layer is depleted as copper diffuses into the layer, and eventually the surface consists of Cu_3Sn which looks like dirty copper and is quite unsolderable with normal fluxes. This extreme has only been seen at TI when brushing removed all of the solder from the knee of the pad and subsequent baking converted all of the Cu_6Sn_5 intermetallics to Cu_3Sn. Needless to say, these surfaces did not wet at all during flow soldering.

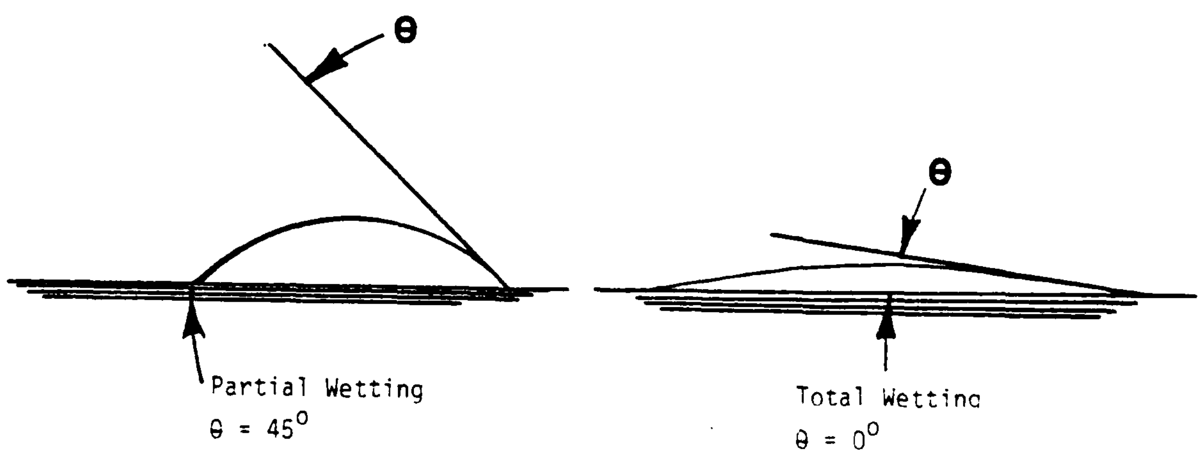

FIGURE 5: Wetting angles on poorly wettable and completely wettable substrates

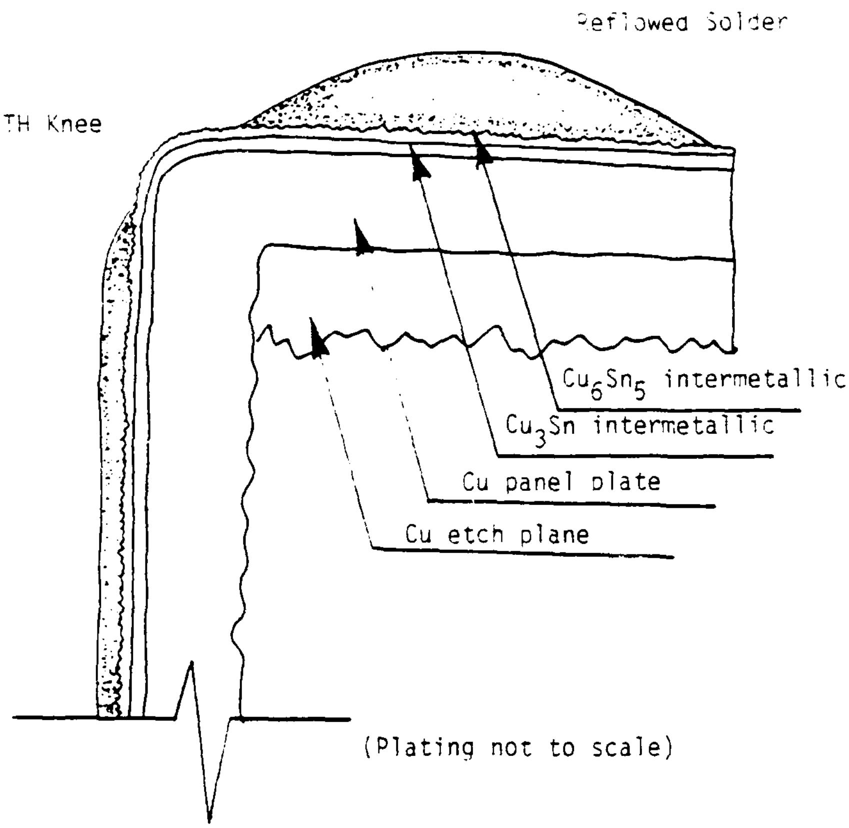

FIGURE 6: Cross-section of a reflowed PTH knee with exposed intermetallic.

The previously described PWB Shop screen, in which one board from a lot is flow soldered without components, is effective in catching lots with extensive bare intermetallics at the barrel knee. The criteria for acceptance are as shown in Figure 2. Unacceptable lots are scrapped since no acceptable rework process has been found. We are imposing a final assembly customer specification on the PWB Shop when a PWB Shop normally produces to the less stringent MIL-P-55110D requirements.

PWB SOLDERABILITY SCREENING AND CORRELATION TOOLS

The PWB shops perform their screening on Electrovert Minipac machines which must model, as well as possible, the larger Electrovert Ultrapak 737 machines most common on TI assembly lines. It is not uncommon for a PWB engineer to be attempting to obtain correlation between results obtained with a bare PWB on the PWB Shop Electrovert Minipac with those of an assembly Process Engineer obtained with stuffed PWBs on an Ultrapak 737 on the assembly floor.

The solderability of PWBs and PWB assemblies is difficult to measure because of the effects of the process and process materials on solderability and because of the interactions between the components and the PWB. Each division of the Equipment Group has its own Process Engineering staff, a distinctive product mix, its own customers, and a distinct heritage and history. There is, of course, a strong commonality and excellent communications between the Process Engineering groups. However, interpretation of the cause for a given solderability problem can vary widely.

The cause for a problem must be rapidly ascertained so corrective action may be initiated and it is helpful if all parties involved have confidence in the evaluation. This is particularly true in the case of marginal PWB solderability resulting from varying degrees of intermetallic compound exposure.

In response to the need for correlation between the PWB Shop's screen and the assembly line's observations, the Materials Analysis Laboratory has designed and built a computer controlled flow soldering machine based on the intermediate sized Electrovert Econopak 229 wave soldererering machine and a Texas Instruments TMS990 microcomputer system. This machine, which is free from manufacturing schedules and constraints, is available to the PWB and Process Engineering community for screening verification and solderability correlation work. It is also used for flux, solder, and process parameter evaluations.

The computer controlled flow soldering machine is set up with the mask shown in Figure 7 where the range of each parameter is part of the mask. A column has been added to the right of the mask showing the tolerances to which each parameter can be controlled. Both flux and wave height are measured directly at the peak of the wave.

PROSPECTS FOR IMPROVEMENT

Texas Instruments PWB engineering group is performing extensive tests on the effects of tin-lead ratio and thickness on the behavior of the molten tin-lead during reflow. MIL-P-55110D allows a tin content ranging from 50% to 70%. These tests are determining whether the pasty range in the non-eutectic high lead compositions might maintain a more uniform tin-lead thickness during reflow. It has been shown that the quantity of tin-lead on the surface during reflow is critical. If there is too little, the knee may be left bare. If there is too much, the PTHs may fill during reflow.

```
Enter TI Part Number:
(________________)
                                                                TOLERANCE

Board thickness..................(0.000-0.360 IN) - 0.___          NA
Conveyor speed...................(1.6-5.3 FT/MIN) - _._      +/- 0.1 Fpm
Conveyor angle...................(1.0-6.0   DEG ) - _._      +/- 0.01°
Board depth in the flux wave.....(0.000-0.500 IN) - 0.___    +/- 0.010
Board depth in the solder wave...(0.000-0.500 IN) - 0.___        0.005
Solder wave height...............(0.001-0.500 IN) - 0.___    +/- 0.005
#1 Upper preheat platten temp....(200-800   DEG F) - ___     +/- 5°F
#1 Lower preheat platten temp....(300-999   DEG F) - ___     +/- 5°F
#2 Upper preheat platten temp....(200-800   DEG F) - ___         NA
#2 Lower preheat platten temp....(300-999   DEG F) - ___         NA
Solder temperature...............(400-550   DEG F) - ___     +/- 5°F
```

FIGURE 7: PWB Parameter Entry Mask

MIL-P-55110D

The language of MIL-P-55110D does not sufficiently define the nature of the reflowed surface to obtain solderability. It quite correctly does not call for a given thickness of tin-lead on convex surfaces such as the knee of the barrel because nature does not encourage liquids to sit on convex surfaces. However, requiring "coverage" of the basis metal without defining the cover leaves too much to the interpretation of the beholder. The user would prefer solder. The PWB vendor might prefer intermetallics. Definition of "coverage" in MIL-P-55110D might be better defined in light of assembly specifications.

SUPPLEMENTARY FLOW SOLDERING SUPPLIES

The solderability of a PWB or a PWB assembly is strongly affected by the components, solder, and flux. In some cases the military specification is excellent and industry can conform to the requirements. In a significant percentage of cases, the applicable military specification is not consistent with the final assembly military specification.

BAR SOLDER

Bar solder is purchased to QQS-571E, which we have found to be an excellent specification for bar solder. The Equipment Group's Materials Analysis Laboratory samples and analyzes to QQS-571E. In 1981 and early 1982, the bar solder rejection rate to QQS-571E was over 36%, as seen in Table 1.

TABLE 1 - BAR SOLDER 1-1-81 TO 10-1-82

VENDOR	LOTS TESTED	LOTS FAILED	NONCONFORMING CONSTITUENT
1	14	8	Cd, Cd, Sn, Cd, Sn, Sn, Sn, Sn
2	25	7	Sb, Sb, Sb, Sn, Ag, Ag, Ag
3	1	0	
4	1	0	

Will Willoughby points out, "You get what you accept." Another truth is that rejected shipments communicate far more effectively to vendors than do memos and verbal complaints. Solder not satisfying QQS-571E has been used in the past on commercial product lines. Our bar solder vendors fell into two groups; those who were selling what we accepted, and those who wondered why they got so little of our business.

In September of 1982, TI focused on solder analysis techniques as performed by TI and our vendors. Each of the seven potential vendors was

invited to send their primary analytical chemist to review our mutual sampling and analytical techniques. The visits were very valuable. Not only was an excellent rapport established, but TI was able to improve several analytical techniques and the different techniques of the vendors were understood and recorded. All of the vendors use analytical techniques that are very similar to those used by TI, except in the case of antimony where either wet chemistry or atomic absorption are used. Solder manufacturers tend to analyze a button poured from the melt rather than the final product. This is a valid technique for impurities. However, segregation in large billets can result in significant error for extended products.

The success of this program is seen in Table 2, where the accept rate of 87% since October 10, 1982 is excellent considering the number of vendors involved and the stringency of QQS-571E.

In summary, TI now supplies all of the Texas divisions with QQS-571E bar solder from several reliable vendors. Our communication lines are now clear and honest.

TABLE 2 - BAR SOLDER 10-10-82 TO 1-5-83

VENDOR	LOTS TESTED	LOTS FAILED	NONCONFORMING CONSTITUENT
2	10	2	Sn, Sn
3	5	0	
4	7	0	
5	12	4	Sn, Sn, Sn, Sn
6	11.	0	

WIRE SOLDER QUALITY

TI currently samples wire solder to QQS-571E, but the rejection rate is very high (around 70%). As previously noted, TI has used much of this solder on commercial products. It is often excellent solder. It is just not the 63-37 QQS-571E solder required by our drawings.

Table 3 shows the results from all lots of wire solder analyzed to QQS-571E in 1982. The acceptance rate is little over 30%. Detailed examination of the results of the analyses reveals one vendor who can control flux levels but whose tin content varies widely within lots. Another has trouble controlling flux content, but has extremely tight distribution of flux and tin within lots. Two vendors fail only on the low tin side because they target approximately 62.75% rather than 63.0% tin. One vendor fails equally on the high and low sides and targets 63.0% tin.

The lack of reproducibility in tin content has been traced to segregation during solidification in the large billets cast to be extended into wire

solder. The large grains resulting from this relatively slow cooling and segregation result in variance in tin content of two percent in the case of wire extruded from the largest billet cast for solder wire drawing. On the other hand, variation of no more than 0.2 percent in tin content among five rolls of solder are seen from the smallest billets cast for solder wire drawing. The Collin equipment, with small billets and a carefully designed solidification process, produces excellent uniformity in the final wire.

Flux content control problems result from the tendency to measure flux content of the drawn wire at a relatively large diameter and then to assume that this flux content will remain constant as the wire is drawn smaller. Again, one vendor tends to be low while another tends to be high.

Now that the cause for variance in tin content within lots is understood and communications have been clearly established with the vendors, the acceptance rate to QQS-571E is expected to approach 100%.

TABLE 3 - WIRE SOLDER 1982

VENDOR	LOT #	PASS/FAIL	SPECS	NONCONFORMING CONSTITUENT (WT%)
1	1	F	2.7-3.9	FLUX = 2.29, 1.82
1	2	F	2.7-3.9	FLUX = 2.11
4	1	P		
4	2	F	62.5-63.5	Sn = 61.7, 62.1, 61.5, 62.7, 62.8
4	3	F	62.5-63.5	Sn = 62.7, 62.4, 62.3, 62.8, 62.5
4	4	P		
4	5	F	62.5-63.5	Sn = 60.8, 61.5, 62.9
4	5	F	62.5-63.5	Sn = 61.3, 61.4, 62.6, 62.2, 61.6
4	5	F	62.5-63.5	Sn = 60.5, 61.7, 62.6
4	6	P		
5	NA	P		
5	NA	P		
5	NA	F	62.5-63.5	Sn = 63.2, 62.1, 62.1
5	1	F	2.7-3.9 0.015 MAX	FLUX = 4.0, 4.0, 4.0, 4.0, 4.0 & Ag = 0.021, 0.021, 0.021
5	2	F	62.5-63.5	Sn = 63.0, 62.8, 63.5, 63.3, 63.6
5	3	F	62.5-63.5	Sn = 63.4, 63.3, 62.9, 63.2, 63.7
6	NA	P		
6	NA	F	2.7-3.9	FLUX = 1.98
6	1	F	62.5-63.5	Sn = 62.3, 62.3, 62.2
6	2	F	62.5-63.5	Sn = 62.5, 63.2, 62.3, 62.2, 62.3
6	3	P		
6	4	F	62.5-63.5 2.7-3.9	Sn = 62.3, 62.8, 62.5 & FLUX = 2.4, 2.4, 2.4
6	4	F	2.7-3.9	FLUX = 2.5, 2.6, 2.4, 2.6, 2.3
6	5	P		
6	6	F	62.5-63.5 2.7-3.9	Sn = 62.2, 62.2, 62.2, 62.2, 62.3 & FLUX = 2.1, 2.2, 2.1, 3.1, 2.2
6	7	F	62.5-63.5	Sn = 62.2, 62.2, 62.3, 62.2, 62.2

FLUX

The purchase of a limited number of fluxes, evaluated both in production environments and in the laboratory, has resulted in minimal flux problems. Texas Instruments presented the results of an extensive flux study two years ago at the 1981 NWC Soldering Seminar. Continuing studies and manufacturing experience indicate that excellent and well controlled fluxes are available from stable vendors. Our customers insistence on RMA and RA fluxes enhances stability in the flux area. However, more active fluxes might alleviate solderability problems with PWBs and component leads that meet the requirements of their respective military specification but do not solder well enough with Rosin fluxes.

COMPONENT LEAD SOLDERABILITY

Over 30,000 lots of incoming components are tested by the Equipment Group each year to the requirements of MIL-STD-202, Method 208D (with the exception that the water vapor aging test is not used). Lots that fail are not allowed into stock. Where there is a critical need for failed components the lots are tinned and retested before stocking. TI, in general, rejects the notion of tinning components that do not require tinning for three reasons. First, component damage has been traced to tinning errors. Second, tinning costs time and money. Third, 100% customer tinning reduces the motive for vendors to produce solderable parts.

Components destined for NWC programs are tested to MIL-STD-202F, Method 208D, on removal from the warehouse and tinned if necessary. The fact that some parts fail solderability tests on removal from the warehouse has been shown to be the result of the very small sample sizes and the subjective nature of solderability, and not due to degradation of the tin-lead surfaces at ambient temperatures in the warehouse. Several tests have shown no degradation of component solderability even on 10 year old components. Current data on the effect of storage on PWB solderability shows no degradation.

Of course, silver leads and porous gold plated leads do not withstand storage well. A general rule is that poorly solderable parts that slip into the warehouse are poorly solderable when removed from the warehouse.

Several years ago, when the incidence of poorly solderable components seemed to be rising rapidly, one engineer was assigned the task of reviewing incoming solderability testing techniques and hold tags, (rejections). Previously each component engineer had been responsible for the solderability of his components. Focusing the primary solderability responsibility in one engineer resulted in effective control of component lead solderability. TI still has specific component solderability problems, but they are specific problems that can be attacked and corrected and not general problems.

MIL-STD-883B, Method 2003.2, only requires 90% solder coverage. MIL-STD-750B, Method 2026.3, only requires 90% solder coverage. MIL-STD-202F. Method 208D, which is the basis for TI's internal and incoming tests, does call for 95% coverage and gives pictures as reference points. The military specifications governing component lead solderability are not always consistent with those governing assemblies.

Where component manufacturers are allowed to sell components with leads that may be unsolderable over 10% of their surface, it is apparent that some of those same leads will not form acceptable fillets in the PWB assembly. However, the final assembly specification, MIL-WPN-6536D for example, does not allow 10% of the solder joints to exhibit lack of wetting of the component lead.

SUMMARY

The military specifications controlling PWB solderability and component lead solderability are not consistent with the final assembly specifications.

Flux, bar solder, and wire solder military specifications are acceptable.

The PWB, which is the critical component affecting PWB assembly solderability, is afflicted with two defects, barrel voids and exposed intermetallic compounds, that are poorly controlled by MIL-P-55110D. Thus, PWBs must be screened to specifications much more stringent than MIL-P-55110D if the PWB assemblies are to meet the assembly specifications without extensive touch-up.

Piece part specifications should be at least as demanding as final assembly specifications.

ABSTRACT

Automatic Insertion in Military Industry

Prepared By

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220

Industry today, with its high technology and high production output requirements, dictates automatic equipment and sometimes specialized equipment to stuff printed wiring board assemblies. There are many types of machines available on the market that will satisfy industries' needs. Here at Raytheon, Lowell, the USM Dyna/Pert systems are used for our automatic insertion needs.

Each of the machines will be discussed separately for capability requirements and updated improvements that make automatic insertion improvements simplified, improve rates and reliability.

The following categories will be further discussed by section:

USM Gravel Component Taping Machine

USM Component Sequencing Machine

USM Controller System 8000

USM DIP Inserting Machine

USM VCD Inserting Machine

USM Gravel Component Taping Machine
Model P2-GU-W-VA FIG. #1

This machine is a bowl feed inline machine equipped with diode polarity checking and reel taping for various types of axial lead components. The main features of discussion are:

- -- Bowl Feed FIG. #2.
- -- Lead Straightening FIG. #3.
- -- Diode Polarity Orientation FIG. #4.
- -- Capacitor Polarity Testing (in development).
- -- Adjustable Output Pitch FIG. #5.
- -- ~~Adjustable Output Pitch FIG. #5~~.
- -- Taping Unit FIG. #6.
- -- Rates.

USM Component Sequencing Machine
Model UCSM-B FIG. #7

This machine is an inline type machine controller by PDP-8000 controller that cuts and dispenses axial lead components from various component reels, and organizes them in a sequential order on a conveyor chain.

The conveyor delivers the component to a verifier test station, performs value verification, optical inspection and, then to the taping unit. That completes a sequenced reel.

Other areas of importance are:

-- Computer Control Unit FIG. #8.

-- Component Verification FIG. #9.

-- Component Inpsection FIG. #10.

-- Station Dispensing Unit Automatic Advance FIG. #11.

-- Rates.

Dyna/Pert System 8000 Machine Controller FIG. #12

This system is a Digital Equipment Computer PDP-8 with 32K memory, equipped with a floppy disc for program storage. This Controller controls:

-- (1) VCD Dual Head Insertion Machine FIG. 13.

-- (1) DIP Single Head Insertion Machine.

-- (1) 60 Station Sequencer for Program Storage.

-- CRT Display with Keyboard.

-- Line Printer.

-- Management Information.

USM DIP Inserting Machine
Model E/K2 FIG. #14.

The USM Dual Inline Package Inserting Machine is a single head 60 channel random access machine that selects, forms, tests, and inserts 6 to 20 lead dual inline package devices on a .300" span.

Areas of concern are:

-- Insertion Area FIG. #15.
Single Table.

-- Cut and Clinch Unit FIG. #16.

-- Single Head FIG. #17.

-- Test Fingers.

-- Optical Correction System FIG. #18.

-- Repair.

-- Single Board and Panel Concept FIG. #19.
Bad Board Override.

-- Rates.

-- Reliability.

USM Valuable Center Distance Inserting Machine
Model E/K2 Dual Head System FIG. #20.

This machine is designed to insert sequenced axial lead components of varying dimensions and lead hole spacings into printed circuit boards. In order to accomplish this, many areas of this equipment must function with utmost precision and speed. Areas of discussion are as follows:

-- Insertion Area FIG. #21.
  Single and Dual Tables.

-- Cut and Clinch Unit FIG. #22.

-- Single and Dual Head FIG. #23.

-- Optical Correction System Dual Head FIG. #24.
  Reprogramming.

-- Panel Concept FIG. #23.
  Bad Board Override

-- Rates.

-- Reliability.

830TP0001

PLATING EFFECT ON COMPONENT SOLDERABILITY AND SOLDER JOINT STRENGTHS

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February 1983

Prepared for Presentation at
7th Annual Soldering Technology Seminar
Navy Weapons Center
China Lake, CA.
February 23, 1983

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PLATING EFFECT ON COMPONENT SOLDERABILITY AND SOLDER JOINT STRENGTHS

by R.N. Wild
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Seventh Annual Soldering Technology Seminar

Navy Weapons Center

China Lake, CA

ABSTRACT

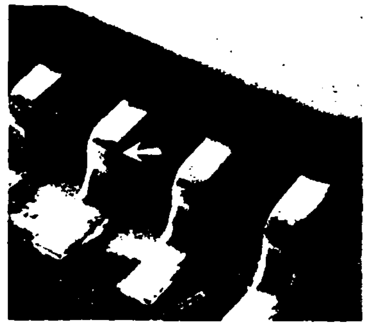
This paper will discuss some serious component solderability and IC solder joint degradation problems that were eventually shown to be related to inadequate specification and manufacturing controls of IC component lead plating parameters. Presently, one cannot procure tin plated hardware to MIL-M-38510E and be assured of adequate plating quality for military product. The primary problem with many component tin and tin lead plating parameters is excessive co-deposition of tin plating organics, even with the stated "matte" tin platings. These co-deposited plating organics are considered detrimental to both component solderability and solder joint strengths, especially when the components are exposed to typical high temperature component manufacturing burn-in operations.

This paper also makes recommendations as to possible modifications of MIL-M-38510E that would significantly change some important component plating parameters that would result in reductions in solderability and reliability problems by the military users.

1.0 INTRODUCTION

Over the last year an increasing amount of solder delamination (flaking) was observed on some military IC flat pack product after pretinning and forming of the flat pack leads for surface mounting of the components (Figure 1). The severity of solder flaking was found to vary from one IC (flat pack) manufacturer to another, and from different date codes of a manufacturer. An increase in thickness of the solder coating (or the tin plate on the leads), or a reduction in the radius of the lead forming bend also increased the propensity for flaking of the lead coating. The as-received tin plated leads would also flake on lead forming, but not as severe as with the thicker and stronger SN63 solder dipped coatings.

Typical Formed Leads No Flaking



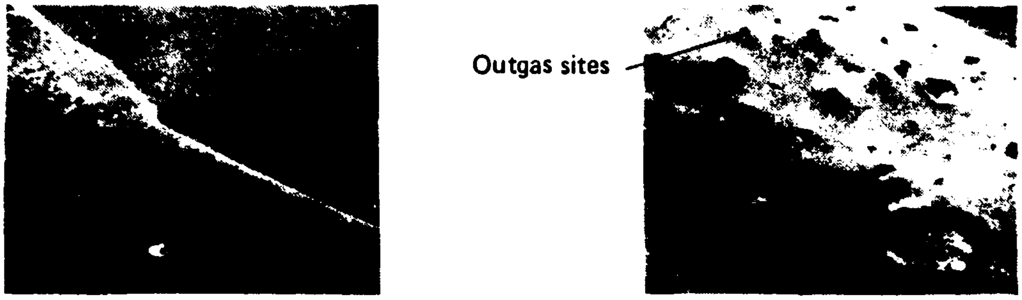
Typical Leads Exhibiting Flaking

Figure 1. Solder Flaking from IC Flat Pack Leads

Most of the components exhibiting flaked leads were originally acceptable to the applicable military specifications for both solderability and plating adhesion. There were some dewetting problems in the areas of worst case flaking; however, our primary concern with the flaking of these leads was the mechanical strengths of the surface mounted solder joints. Solderability was still of some concern as some special solderability experiments by the Tin Research Institution showed a reduction in solderability with multiple soldering exposures. One other early observation with the tin platings that eventually led to solder flaking was a tendency of the original tin plating to outgas to varying degrees on tin reflowing. Later discussions will be made with this issue.

2.0 REVIEW OF SOME PERSISTENT SOLDERABILITY PROBLEMS

Many erratic but persistent component solderability problems over the last several years have resulted in IBM Owego pretinning nearly all incoming components to improve both component aging in storage (shelf life) and to reduce soldering defects during hardware assembly. This pretinning, although expensive and time consuming, appeared effective in overcoming most plating problems (oxidation, lead contamination and the severe outgassing problems found with many bright tin platings, see Figures 2 and 3).

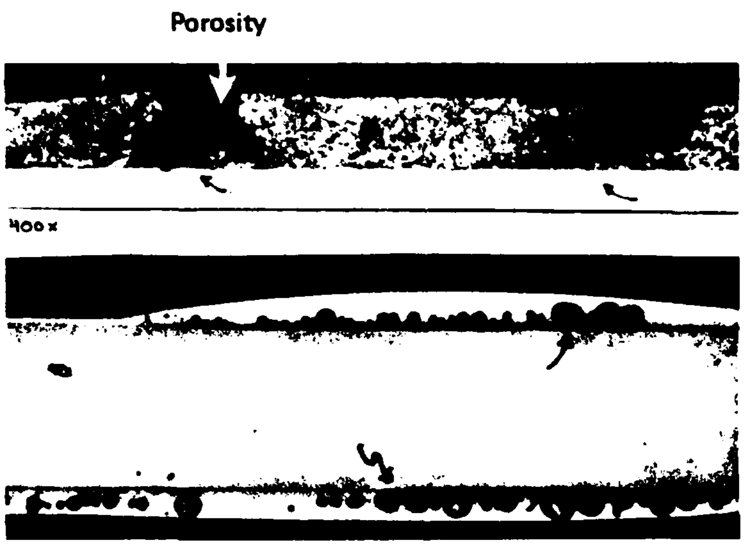


20 X

190 X

Note severe outgassing of plating organics
when tested to Method 208 of MIL-STD-202.

Figure 2. Typical DIP Solderability Problem (Bright Tin Plating)

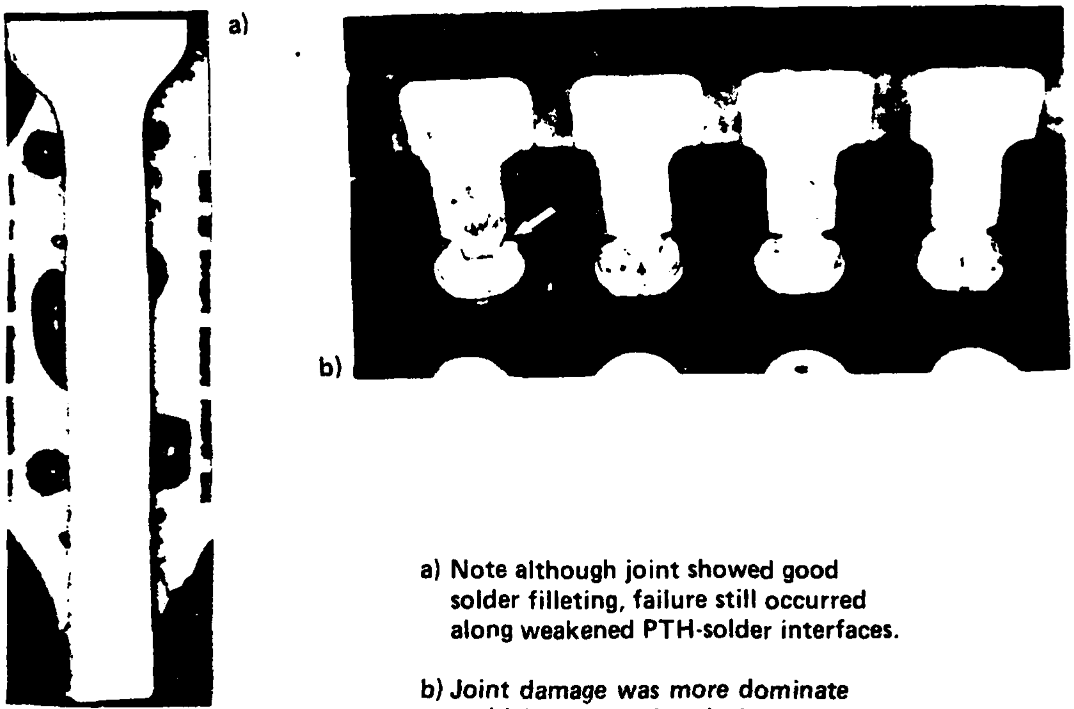


150X

Note both porosity and
voids in solder coating.

Figure 3. Sectioned Leads

As an example, the major reasons for our pretinning of all "DIPs" prior to assembly was both to reduce basic solderability problems and to reduce component outgassing of entrapped plating organics which were occurring in assembly. These outgassing reactions have also created some significant thermal cycling solder joint failures in the past due to weakening of plated-through-hole (PTH) solder connections by gaseous solder void formations during soldering. A typical failure, shown in Figure 4, was on a larger higher stressed side brazed 40 I/O pin DIP. This solder joint failure occurred rather early in $-55^{\circ}C$ to $+105^{\circ}C$ thermal cycling (~100 cycles). This failure was caused by rapid solder crack propagation along the higher stressed pin to solder interface, caused both by the gaseous solder voids and the rather high thermal expansion mismatch with these types side brazed leaded components populated to multilayer boards (MLBs).



a) Note although joint showed good solder filleting, failure still occurred along weakened PTH-solder interfaces.

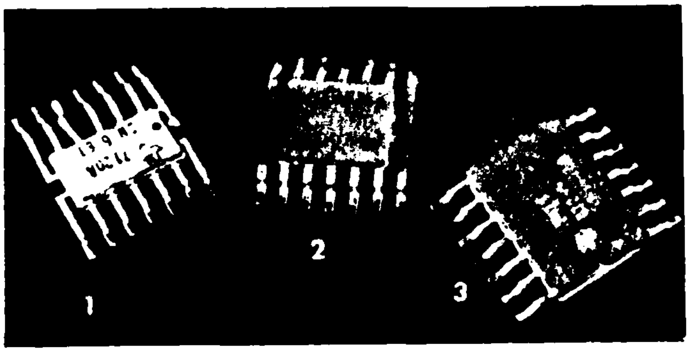
b) Joint damage was more dominate on higher stressed end pins. ("X" directional strains.)

Figure 4. Typical DIP Solder Joint Failure

Although the tin plating outgassing reactions shown in Figures 2 through 4 were reduced by the change in MIL-M-38510E to allow only matte tin platings, there is still very severe outgassing reactions with many present "stated "matte tin platings.

3.0 SPECIFIC IC FLAT PACK FLAKING PROBLEMS

The basic concerns with the solder flaking found on IC flat pack leads were 1), the minor (in most cases) exposure of the Alloy # 42 lead material and 2), more important, the possibility of developing weaker IC solder joints. The strength requirements for surface mounted flat pack solder connections have increased over the last several years due primarily to the evolutionary change in flat pack configurations which has produced larger bodied, higher stressed component lead configurations (Figure 5).



1) Low Stress Configuration

2) Higher Stress Configuration

3) Highest Stressed Configuration

Figure 5. Some Flat Pack Stress Configurations

Very early engineering studies, with surface mounted flat packs, showed that the lead form, the solder process, and solder joint configurations, were all very important as to assuring acceptable low stressed solder connections. As known in industry, these types of solder connections are generally considered weak due to possible stress rupture(creep rupture) loadings. This would be especially important with excessive spring loading of the solder joints (Figure 6).

Joint Loading = ~ 700 psi
(Joint tensile peel loading)

Joint Loading = ~ 600 psi
Failure in ~ 350 hours
(Joint shear loading)

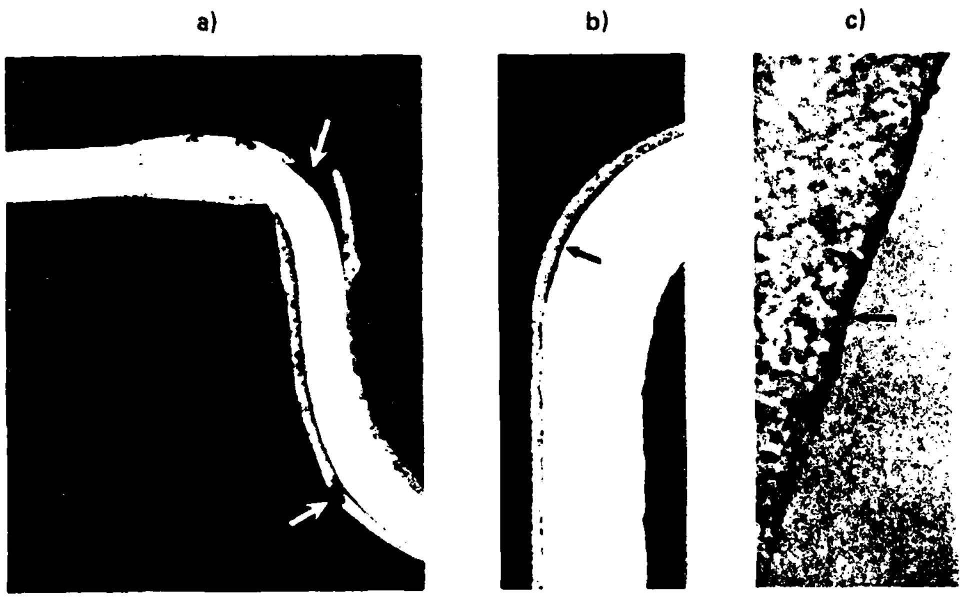
Note: **Great care is taken to prevent soldering deformed leads in spring loaded position**

Figure 6. Spring Loaded Solder Joint Stresses – Failed Joints (SEM of Stress Rupture Failures)

5.0 FLAT PACK LEAD ANALYSIS

Metallographic analysis of the lead flaking conditions showed, in general, very clean solder (or tin plating) separation from the Alloy = 42 lead "interface" on lead forming. As shown (Figure 11), some of this flaking could lead to potentially weak solder connections due to joint stress concentrations at the bottom lead form bend. This analysis also showed an unusually thin and irregular nickel-tin (Ni Sn) intermetallic alloy formation along these soldered interfaces. This was very unusual as vendor high temperature burn-in and subsequent pretinning operations would normally develop a more uniform and thicker (Ni Sn) intermetallic alloy bond layer along this interface. The weaker the connection or the more the lead flaking, the less noticeable was this Ni Sn alloy layer (Figure 12). This lack of a continuous Ni Sn layer was additional evidence that something was present at the Alloy # 42 interface preventing normal development of the Ni Sn intermetallic interface layer during burn-in and soldering.

Metallographic analysis of the as-received "tin "plating conditions failed to show any obvious tin to solder interface problems with optimum resolution to ~ 1200X magnifications. The analysis did show some foreign particle inclusions in the tin plating which we believe to be entrapped organics from the original tin plating operations (Figure 13).



This analysis showed very weak solder-lead interface conditions. Photo a) shows potential stress concentrations due to cracking. Photo c) shows a weak intermetallic interface.

Typical Lead Flaking

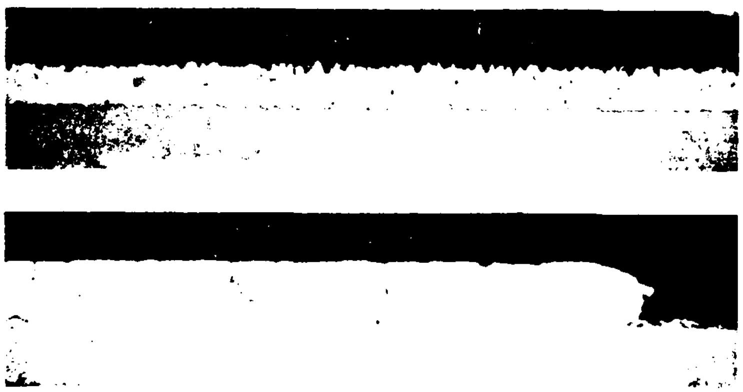
Failed Interface

Figure 11. Metallographic Analysis – Flaked Leads

Tin plating - etched
Note no evidence of Ni Sn intermetallic alloy layer on this weak interface.

Stronger interface
Stronger interfaces generally showed more evidence of Ni Sn alloy layer.

Figure 12. Metallographic Analysis – Interfaces



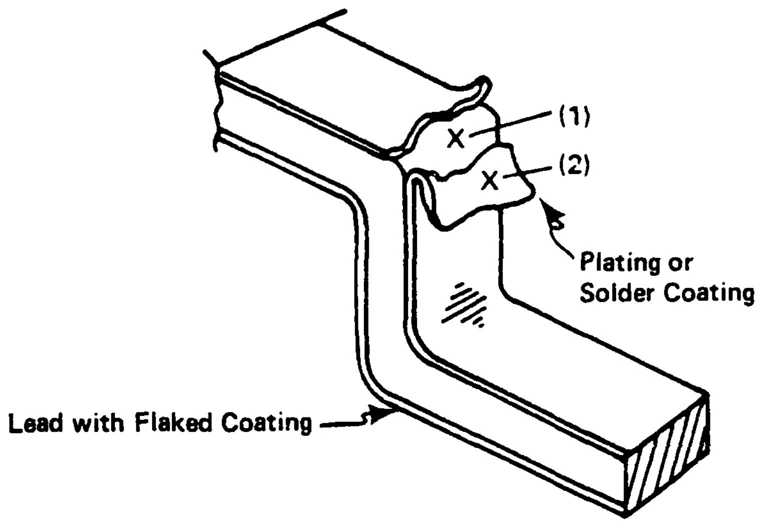
a) Note entrapped organics plating inclusions.

b) No obvious defects at tin to Alloy # 42 lead interfaces.

Figure 13. As Received Tin Plating Conditions (Matte Tin)

6.0 MICROPROBE AND AUGER SURFACE ANALYSIS

Macro examinations of the flaked lead conditions showed a matte brown to dark grey appearance of the fractured surfaces. Microprobe analysis early in this study showed an unusually high concentration of carbon present on these fractured (flaked) surfaces (Figures 14 and 15). The more severe the flaking and the darker the fractured surface, the more evidence of carbon being present. Auger surface analysis (Figure 16) supported the microprobe analysis findings. There was also oxygen present on these fractured surfaces. but was not considered the primary cause of the weak interface conditions.



Typical Surface Analysis:

1) Substantial carbon, some tin, little evidence of oxidation
2) Carbon, then Tin-Nickel-Iron (intermetallics) separated from lead surface)

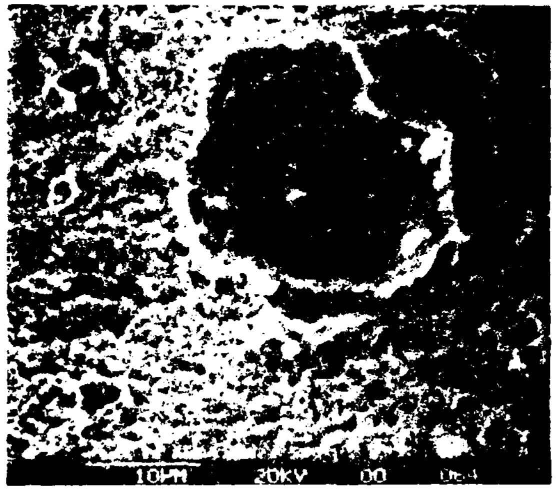
Note:
- o Carbon, not oxidation was major contributor to weak lead to solder interfaces. (Three major suppliers)
- o Metallographic analysis cannot resolve defects on unformed lead interfaces. Thin non-uniform intermetallic layer, found on weak leads.

[Weakest joints shows darker lead surface in flaked area. Also analysis shows highest carbon content on weakest leads.]

Figure 14. Microprobe and Auger Analysis – Weak Lead Interfaces

Clean Solder Separation from
Alloy = 42 Lead Interface

Arrow shows flux entrapment
under lead



Carbon was most prominent contaminate
at fractured interface

Figure 15. Fractured Weak Lead Interface (Bottom of Lead)

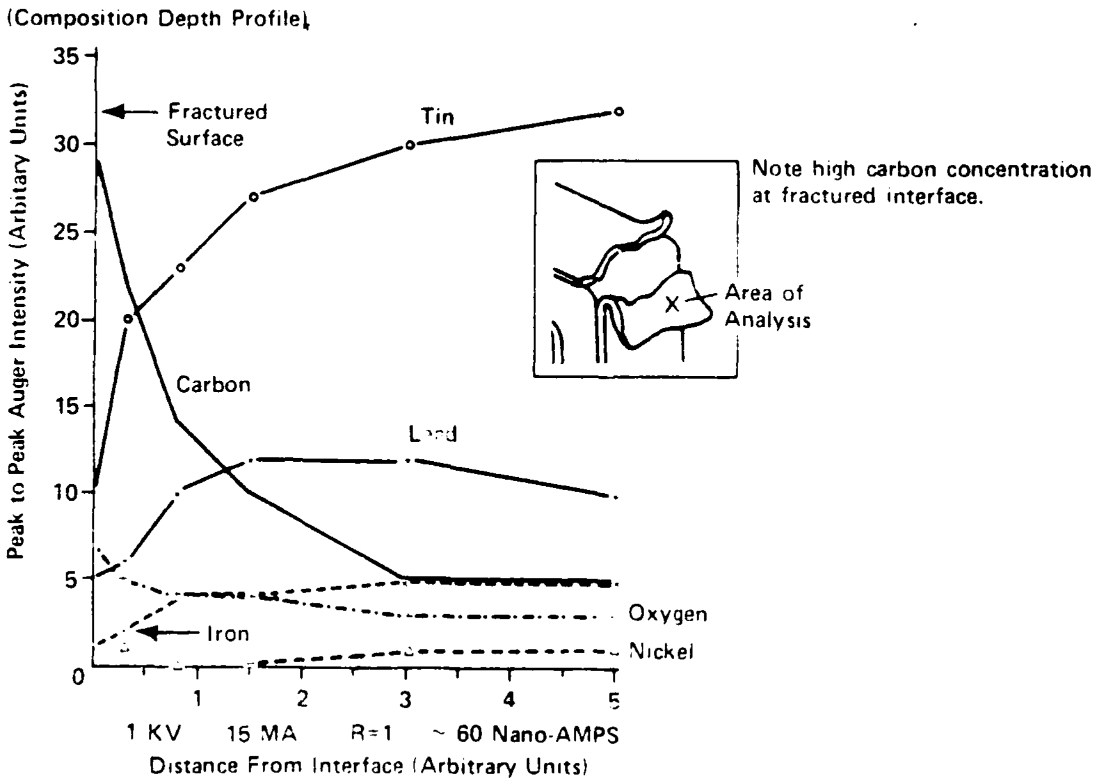


Figure 16. Typical Auger Surface Analysis

7.0 TIN PLATING REACTIONS

All analysis and test data to this point (original tin outgassing on reflowing, solder dip tinning experiments, metallographic, Microprobe and Auger surface analysis) indicated original tin plating parameters as being the primary cause of flat pack lead flaking and weak solder joint connections. Technically, we believed that interface material reactions with entrapped tin plating organics (Figure 13) was the most likely source of carbon being detected at the weak tin to solder interface connections. These reactions, although not as obvious, were believed to be very similar to that shown by previous investigators (1) (2) and IBM with some tin and acid copper platings (Figure 17).

In these experiements, serious solder to acid copper plating interface degradation occurred with high organic content in the acid copper platings when aged at elevated temperatures (> 100°C). This solder to acid copper interface degradation was believed caused by both interface (in these cases Cu Sn) oxidation and carbon contamination creating interface void formations at high temperatures. This is believed to be an elevated temperature diffusion mechanism with entrapped plating organics, most likely via Kirkendahl voids as the organic molecules are believed too large to move by other diffusion mechanisms. This diffusion mechanism would vary with different metallic systems, with the tin to Alloy # 42 (primarily nickel) system not being nearly as obvious as shown with some tin to acid copper plating systems (Figure 17). The actual analysis of the organic contamination is presently unknown due to the very small concentrations and the difficulty of analysis.

A. Normal Interface Reactions

B. Interface Degradation

Photo A: **Shows normal development of Cu Sn intermetallic compound formation at the solder/copper interfaces. Note no interface void formation.**

Photo B: **Shows serious copper interface degradation during a 150°C aging test. This serious interface voiding will eventually cause failure through complete interface separation during elevated temperature aging.**

Figure 17. Sulfate Copper-Aging Effects – Organic Reactions (48 Hours at 150°C)

8.0 BURN-IN AND REFLOW ANALYSIS

This analysis was conducted on two different groups of flat packs with the lead material coming from two different vendor sources. The analysis was to establish the effect of a typical 150°C component burn-in and the effect of tin reflow prior to this burn-in operation on the tin to Alloy # 42 lead interface. This analysis was to test the previously discussed diffusion theory where we believed that burn-in operations would be deterimental and tin reflow prior to this burn-in would improve the flat pack lead interface strengths. Reflowing of the tin plating prior to burn-in would release some of the entrapped tin plating organics, thus reducing the amount of organics remaining for elevated temperature diffusion reactions. This specific test was however made with a fresh improved plating bath (not worst case plating condition). The specific plating test conditions were:

- o As Tin Plated ICs (New Bath)
- o ICs Burn-In 88 Hours at 150°C
- o Tin Reflowed Prior to Burn-In

All of this test hardware was pretinned with SN63 solder, the IC leads were formed and then the parts were automatically reflow soldered to typical MLBs. The solder joints were then tested for solder joint strengths as per Figure 9.

The test results on both groups of flat packs (Figure 18) showed solder joint and lead interface degradation with the 150°C burn-in operation. The tin reflow prior to burn-in was proven beneficial however as solder joint strengths did not degrade nearly as much as the normal burn-in without tin reflowing. This was especially noticeable with the weakest solder connections (1.0 vs 2.0 lbs pull strengths).

We believe this test will at least support the tin plating organic contamination theory and also we must remember that these tests were conducted with an improved tin plating bath.

Test Conditions	Solder Joint Strengths = Average (min-max)		Average Strength Pounds
	14 Leaded Flat Packs	16 Leaded Flat Packs	
o As Tin Plated	4.24 (3.3 to 5.6)	4.36 (3.8 to 6.2)	4.30 (3.3 to 6.2)
o Tin Plated + Burn-in (88 hr @ 150°C)	2.27 (1.1 to 3.7)	2.34 (1.0 to 3.8)	2.30 (1.0 to 3.8)
o Reflowed Tin Then Burn-in (88 hr @ 150°C)	2.78 (2.0 to 4.3)	3.06 (2.1 to 4.6)	2.92 (2.0 to 4.6)

Figure 18. Effect of Burn-In and Tin Reflowing (Mechanical Tests)

9.0 SPECIAL PLATING TEST

Due to finding substantial differences in flaking and lead solder joint strengths from one production lot of ICs to another and from one vendor to another, we needed a more economical and a more accurate inspection test to determine plating quality of incoming hardware. Again, the normal military hardware testing was proven inadequate as to screening for the plating defects shown in this paper, and the mechanical tests were considered too expensive and time consuming for normal receiving inspections.

A very simple tin reflow test was eventually developed where an operator could easily detect degrees of outgassing on reflow of the different tin platings (Figure 19). The degree of outgassing generally correlated to both lead flaking and solder joint strength. These tests showed substantial variations in degrees of outgassing, again from one vendor to another and one IC date code to another. In general, the worse the outgassing found, the more the evidence of lead flaking and the lower the joint strength. Some plating showed no significant outgassing while others showed major outgassing reactions (Figure 20).

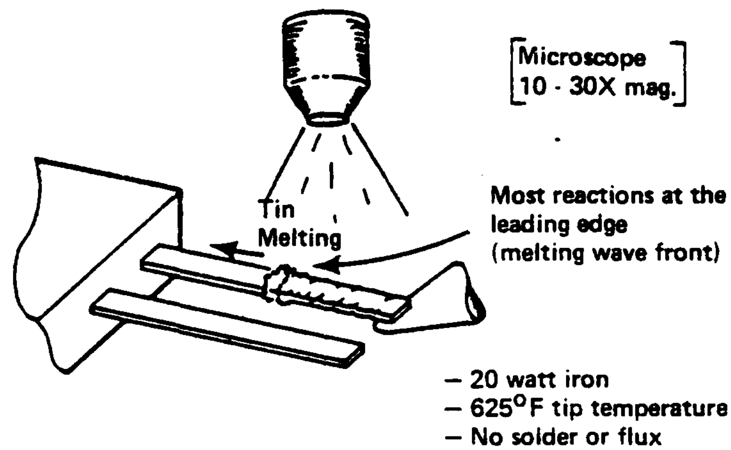
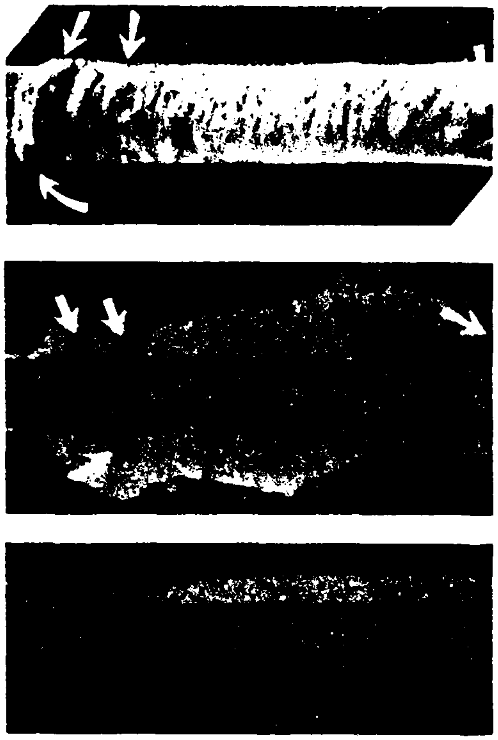


Figure 19. Tin Plating Outgassing Test



a) Typical outgassing, note surface disruptions on reflowed tin.

1) Melting front.

b) More severe condition, not worst case.

2) Voids.

c) No significant outgassing found with "Wren" tin plating bath plus at least one other plating bath or process.

Figure 20. Variations in Tin Outgassing on Reflowing

This tin reflow test, although not quantative, is very easy to conduct and would be considered beneficial to use for various tin and tin-lead plating lines to monitor plating parameters such as entrapped plating organics.

Presently MIL-M-38510E states that no co-deposited organics are allowed in "matte" tin platings. Obviously this requirement is very severe and it is also obvious that it is being ignored by many manufacturers. Until MIL-M-30510E provides a realistic limit on the maximum carbon content allowed in the various platings, this plating outgassing test would at least be useful in screening out worst case, as-received, or in-line defective product.

Other users throughout industry have shown that the same type of entrapped plating organics are still causing serious solderability impacts with military product. Mr. J. McCormick of RADC has had substantial work underway, over the last year, with key industry and technical contacts to develop a method to establish the clear difference between bright and "matte" tin platings and to address the effects of reflowing of tin platings to overcome some of the present tin plating concerns. Mr. W. Holson, of the Navy Avionics Center, has also been working on various methods to establish organic limits for tin platings. These methods include similar outgassing tests and gaseous carbon analysis.

10.0 OVERALL SUMMATION/CONCLUSIONS:

Presently we (the users) cannot procure tin plated hardware to the requirements of MIL-M-38510 and be assured of adequate plating quality for military product. The basic problems are:

- o Constant long term solderability problems, forcing many users to pretin most, if not all plated products used on military hardware. Certainly this is not cost effective to the military or other users of this product.

- o Some procured product meets all solderability specification requirements yet shows serious de-degradation of resultant solder joints.

- o Entrapped plating organics in "stated" matte tin platings appears to be a major problem with many component manufacturers. The matte tin plating requirements of MIL-M-38510 are either not properly understood or some requirements are being ignored.

- o The basic IC flat pack solder flaking and solder joint strength problem, discussed in this report, are caused by a carbonaceous contamination at the flat pack lead to tin plating interface. The contaminate is:

  - Related to inadequate tin plating parameters; primarily excessive co-deposition of plating organics into the "matte" platings (not true matte tin platings).

  - Component aging at high burn-in temperatures with entrapped plating organics substantially degrades the tin plating to Alloy # 42 interface bond probably by diffusion reactions.

- o Both component burn-in operations and the present minimum tin plating thickness requirements (0.0002") of MIL-M-38510 are believed significant contributors to poor product solderability and resultant low joint strengths, in addition to poor and erratic solderability after storage.

11.0 RECOMMENDATIONS:

- o Requirements of MIL-M-38510 should be strengthened to insure manufacturers' conformance as to providing true "matte" tin platings without entrapped plating organics. Substantial and detrimental plating variations presently exist within industry.

- o The minimum tin plating thickness requirements of MIL-M-38510 should be increased from the present 0.0002" minimum to 0.0004" to reduce some of the detrimental effects of components burn-in operations and to provide better shelf life storage conditions.

- o Maximum, but reasonable organic levels in the tin and the tin lead platings should be established. This can be done by combustion carbon analyses and we believe the maximum level should be set at approximately 0.04 percent carbon.

- o We strongly believe that a proper matte tin plating should exhibit no significant outgassing on reflow of the tin plating. We believe that this should be a requirement of MIL-M-38510E.

- o Industry and the military should consider establishing guidelines and limitations on component burn-in procedures as these burn-in operations can be very detrimental to both lead solderability and resultant solder joint reliability.

- o We generally support the present tin reflow requirements of MIL-M-38510E for the following reasons (with specified reservations):

  - Tin reflowing would be a solderability test in itself at an optimum point for proper correction, if solderability problems develop. (At component manufacture).

  - Reflow of most tin platings (with organics) prior to thermal treatment such as burn-in, would reduce some of the possible entrapped organics in the platings: thus, reducing detrimental burn-in diffusion reactions.

  - A "proper "reflow of tin (and tin-lead) platings " with an adequate lead coverage "should provide very good shelf life for the component user. This has been verified by recent RADC support studies.

  - Reflowing will reduce the potentials for tin whisker growth by reducing plating stresses and by removing plating organics as possible sites for whisker growth.

12.0 ACKNOWLEDGEMENTS:

This overall study was a major effort with many people contributing significantly to various aspects of the study. Some of the most significant IBM analysis contributors however were: Mr. C. Sekora – plating aspects, Mr. R. Wold and R. Musa – processing effects, Mr. W. Dobbin – chemical analysis, Mr. G. Hitt – Microprobe analysis. Mr. J. Cain – Auger analysis. Mr. J. Northrup – vendor interfaces, and Mr. L. Bottsford-Quality effects.

Substantial interfaces, consultations, some tests (T.R.I.) and helpful advice was also received from Mr. J. DeVore and L. Zakrayser of General Electric, Mr. W. Hobson US Navy Avionics Center, and especially Mr. J. McCormick of RADC and Mr. P. Davis and Dr. M. Warwick of the Tin Research Institute.

13.0 REFERENCES:

(1) "Effect of co-deposited organics in plated coatings on electronic hardware reliability;" by J.R. DeVore. General Electric. Syracuse. NY 1981 Solder Technology Seminar. China Lake. CA.

(2) "Optical and Auger Microanalysis of Solder Adhesion Failures in Printed Wiring Boards," by K. Kumar and A. Moscaritolo of the Charles Draper Laboratory. Cambridge. Mass.

24

SOLDERABILITY DEFECT RECOGNITION FOR SOLDERABILITY TESTED COMPONENT LEADS

by

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China Lake, California

ABSTRACT

Many printed circuit assemblies for aerospace hardware are designed to include a variety of components. It is important for the component leads to have good solderability to assure solder joints with good reliability and requiring a minimum of touch-up.

When production schedules permit solderability rejected parts to be returned to the supplier instead of being reworked, it is discovered that the manufacturer often disagrees with the user's solderability rejections. One of the principal reasons for this lack of agreement is that the three applicable MIL standards are not specific enough about the definition and appearance of discrepant solderability tested conditions. As a result of metallurgical examination and analysis of many samples of component lead finishes which resulted in poor quality coating when solderability tested, Litton Guidance and Control Systems has defined a set of five defect conditions with illustrating lead surface photographs.

SOLDERABILITY DEFECT RECOGNITION FOR SOLDERABILITY TESTED COMPONENT LEADS

Introduction

Much of today's aerospace hardware uses several types of components in printed circuit board assemblies. Component leads soldered in plated-through-holes and other part leads soldered to surface pads provide the soldered joint connections. Good solderability is required of these board connection areas and of the component leads as well. The printed circuit board manufacturers and users have made much progress in defining the board solderability requirements and test methods. Much less has been accomplished in standardizing test methods and acceptance criteria for component leads.

Many of the hardware manufacturers or component user companies conduct solderability tests on component leads at Receiving Inspection. When component lots fail the test, production schedules often dictate that the parts be reworked and used if possible. This extra processing, whether done in-house or at an outside process facility, may cost the company thousands of dollars a year. When schedules permit, and the parts are returned to the supplier, it is discovered that the component manufacturer often disagrees with the user's solderability test result interpretations and maintains that the parts are acceptable. In either case, appropriate corrective action is difficult to obtain.

One of the principal reasons for the differences of opinion between the component manufacturer and the user on the conditions that constitute acceptable solderability is that the three MIL standards are not specific enough about the definition and appearance of solderability tested discrepant conditions or defects. There is a need to describe in detail, by simple definitions with associated photo examples or standards, the solderability test failure visual criteria. That is the purpose of this presentation.

Solderability Testing Requirements

MIL-M-38510 for microcircuits references MIL-STD-883, Method 5005 for Qualification and Quality Conformance Procedures which requires solderability testing to MIL-STD-883, Method 2003. In addition, MIL-M-38510 has specific requirements for lead finishes as to types of plating or coating, undercoating, and thickness ranges. Thus the specification has a double safeguard for solderable leads.

MIL-S-19500 for Semiconductors has a requirement for solderability testing to MIL-STD-750, Method 2026. The MIL-S-19500 slash numbers, which specify a particular device type, contain the lead finish requirements which are often given simply as "---gold or tin plated", with no thickness ranges or undercoats. Thus the bulk of the solderability requirement rests with the solderability test alone.

The specifications for passive components such as MIL-R-39005, Resistors, require a solderability test to MIL-STD-202, Method 208. For terminal finish the requirement is "Solderable terminals shall be suitably treated to meet the requirements of solderability". Again,

the solderability test is the sole provision for the solderable quality of the leads.

Mil Standard Requisites

Much of the evaluation work that has been done and the recommended revisions to these standards pertain to the differences in the test conditions such as test temperatures, fluxes, and aging treatments. Consequently little attention has been directed to the definition of the solderability tested defects.

Let us examine how the three MIL standards specify solderability test lead acceptance and rejection criteria.

MIL-STD-883, Method 2003.
This standard, in evaluation of solid wire terminations 0.045 inch or less in diameter, states:

"a. That the termination is at least 90 percent covered by a continuous new solder coating.

b. That pinholes or voids are not concentrated in one area and do not exceed 10 percent of the total area."

Certainly there are defects in addition to pinholes and voids which should be considered in determining if there is a continuous new solder coating.

MIL-STD-750, Method 2026.
This document specifies 90 percent coverage and refers to MIL-STD-202, Method 208 for requirements.

MIL-STD-202, Method 208. This standard, in evaluation of solid wire terminations .045 inch or less in diameter, states:

"a. That the termination is at least 95 percent covered by a continuous new solder coating.

b. That pinholes or voids are not concentrated in one area and do not exceed 5 percent of the total area".

Figures in 208-6 are an aid in the evaluation of the 5 percent allowable area of pinholes or voids and Figures 208-7 are photographs of acceptable leads with solder defects. This standard makes an effort at illustrations but the photos are indistinct and definitions of discrepant conditions are lacking. An example of the insufficient criteria descriptions in this standard occured when we visited a component manufacturer and brought samples of gold plated lead parts purchased from him which exhibited gross dewetting after solderability testing. After examining the leads using a microscope, the Quality Manager stated that there was no evidence of gold showing through the solder, therefore there was a continuous new solder coating as specified in the standard and the parts were acceptable.

Evaluation Of Parts With Poor Solderability

In order to develop suitable solderability tested lead surface criteria, at Litton, we have conducted metallurgical examinations and analyses of many samples of component lead finishes which resulted in poor quality solder coatings when solderability tested. Examples of some of the repetitive types of rejections are as follows:

Nickel-Iron Alloy Transistor Leads With Very Thin Gold Plating

These types of parts have a record of a high percentage rejection of the lots received. Solderability tested sample, Figure 1, shows a lead with poor solder coverage. A SEM photo, Figure 2, of the as-received lead surface indicates the voids in the gold plating which serve as corrosion sites.

Tin Plated Copper and Copper Sheathed (Dumet Type) Diode Leads

This type of lead and finish has a record of frequent solderability rejections. Two types of failure causes within this category when tin is plated on copper and the components are burned in were identified by metallurgical analysis.

Copper-Tin Intermetallic Growth Insufficiently Covered with Tin. These diodes from a particular manufacturer had a record of intermittent solderability rejections of the type shown in Figure 3. Additionally, some of the as-received tin plated parts had a yellowish or golden hue, instead of the conventional gray color of electroplated tin. A cross-section of a lead at 625X, Figure 4, shows a thick, irregular copper-tin intermetallic layer near the surface and even exposed at some points. A microprobe analysis was used to confirm the identification of this layer. Figure 5 indicates the analysis at points A and B to be two copper-tin intermetallics, Cu_6Sn_5 and Cu_3Sn respectively, and point C to be tin.

Copper Plated with Bright Tin Containing Co-Deposited Organic Material. This diode manufacturer plated the copper sheated (Dumet type) leads with tin from a plating bath containing organic brighteners. A substantial percentage of as-received lots failed the solderability test exhibiting a condition shown in Figure 6. Measurement of the mounted lead cross-section coating verified a tin plating of a nominal 300 microinch thickness which should have been adequate to provide acceptable solderability. Examination of JAN TX type diodes which had been burned-in showed a mounted cross-section view of the leads whose tin plating had deteriorated, Figure 7. This damaged tin plating was indicative of a condition often

attributed to organics occluded in the tin plating and expelled forcibly by elevated temperature exposure resulting in inadequate coating protection to provide good solderability.

Tin Plating Directly on Nickel-Iron Alloy with no Nickel Barrier Plating. An example of integrated circuit package leads with this type of finish is shown in Figure 8. Solderability testing frequently results in the defect condition illustrated in Figure 9. As a result of sample analysis from many lots of nickel-iron component leads for solderability test failure, we have determined that a high percentage of the failed lots have no nickel barrier coating under the tin plating. The explanation may be that effective cleaning processes for nickel-iron alloys are not as commonly known as those for nickel so that a more solderable tin plating is generally applied over nickel.

Defining Solderability Defects

By a review of the various analysis conclusions of the causes of poor solderability and the association of these causes with the visual surface defects after solderability testing, we were able to define five categories of poor solderability visual criteria. The definitions of these defects with illustration photos are as follows:

Dewetting. A condition which results when molten solder has coated a surface and then receded leaving irregularly shaped mounds of solder separated by areas covered with a thin solder film; base metal is not exposed. Figure 10 illustrates a dewetted condition. An easily recognizable characteristic of dewetted area is that the molten solder has formed a mound and then pulled back. The visible dewetted area

resembles a crater with the solder at the lip forming a ridge which is ususally higher than the adjacent solder. The crater bottom has a matte finish and may have small beads of remnant solder, whereas the rim solder is usually bright. The craters are often of different sizes even in the same general area.

Nonwetting. A condition whereby a surface has contacted molten solder but the solder has not adhered to all of the surface, base metal remains exposed. The most recognizable characteristic of this condition is that the nonwet areas retain the surface appearance of the lead surface prior to solderability testing because these areas did not wet, or form an intermetallic compound with solder. Figure 11 is a photo of a solderability tested lead with the nonwet areas being the original tin plated surface.

Pinholes Small holes occurring as imperfections which penetrate entirely through the solder layer as illustrated in Figure 12. These voids resemble dewet areas in minute form in that the cavity entrance is usually smooth, shiny solder but the discrepant area is too small to result in the pullback and ridging of dewetting. Pinholes occurring in a particular area, if not too concentrated, are ususally of approximately the same size.

Porosity. A condition of a solder coating with a spongy appearing, uneven surfaces which may contain a concentration of small pinholes and pits. Figure 13 is a photo of an integrated circuit lead exhibiting this condition.

Foreign Material. A lumpy, irregular coating which has covered, or partiall covered, particles of material located on, but different than, the lead material or coating. An example is shown in Figure 14.

Estimating or Measuring Defect Areas

Defect Areas as Related to Individual Defects

In the measurement or approximation of areas not covered by a continuous new solder coating, and using the 5 classes of rejects we have just defined, the visible areas of dewetting, nonwetting, and foreign material are applicable directly. The areas of individual pinholes, or of the pinholes and pits forming the condition of porosity are not themselves measured. These defects, when concentrated in one or more specific areas, make that whole area solderability defective, and therefore that whole part of the surface area is used in calculating or approximating the percentage of the total lead surface.

Defect Area on Round Leads

The measurement of defects, or the estimation of defect area percentage of the lead total surface area, is more difficult with round leads than it is with flat surface rectangular leads. For example, as illustrated in Figure 15, in viewing a cylindrical surface such as a round lead, a round diameter size defect when flat, appears oval shaped and less in width than the visible surface of the lead in the transverse direction, which is half of its circumference.

To aid the solderability test inspector in estimating the lead surface percentage consisting of defects after solderability testing, a set of guide sheets for different diameter round leads has been prepared. In Figure 15, on 0.02" diameter leads, when one inch of the lead surface is inspected for solder coverage, 20 diameter size

defects equal 10 percent of the total lead surface area. Numbers of half diameter size and quarter diameter size defects are also listed. On leads shorter than one inch, the same kind of defect numbers are lsted for 10 percent of the total surface area of a one-half inch lead length.

SUMMARY

Photos of the defect conditions shown in these standards are examples of solderability test failures of the electronic component leads with finishes as purchased by Litton Guidance and Control Systems. Other companies may wish to supplement these standards, within the same defect definition classifications, with photo examples of their own which represent more closely their solderability test failures.

These recommended solderability standards as proposed revisions to MIL-STD-750, Method 2026 and MIL-STD-883, Method 2003 have been distributed for comments to member companies of the G-12 Solid State Devices Committee of the Electronic Industries Association. A set of identical standards has been submitted to the Army Electronics Technology and Devices Laboratory at Fort Monmouth as a recommended revision of MI1-STD-202, Method 208, Solderability. These defect definitions and photos have also been sent to IPC, the Institute for Interconnecting and Packaging of Electronic Circuits, for addition to the first coordination draft of IPC-S-805, Solderability Tests for Component Leads and Terminations.

We have discovered that upon being presented with a technical report describing the cause of a solderability rejection, and a definition and photo of the defect areas, the manufacturer was more receptive in recognizing the problem. To meet the purpose of solderability test visual criteria standardization, an agreement on the defect definitions and appearance is encouraged so that the component manufacturers have a defined set of industry standards for comparison. The use of such standards to obtain corrective action on lead finishes with poor solderability will lead to substantial cost savings for the users.

Illustrations

Figure 1 - POOR SOLDER COATING

Figure 2 - VOIDS IN GOLD PLATING

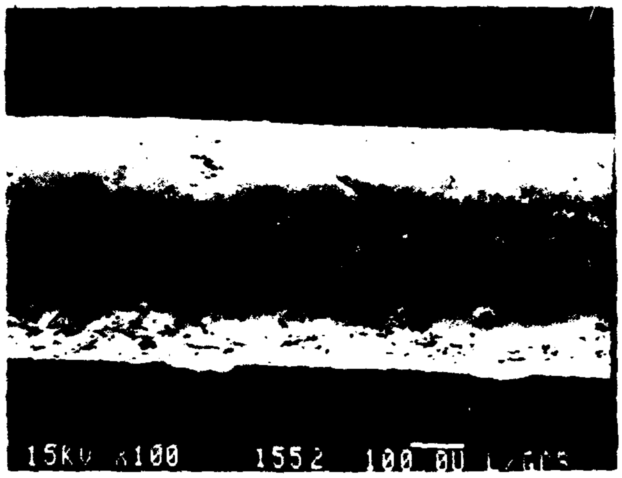


Figure 3 - POOR SOLDER WETTING

Figure 4 - INTERMETALLIC BETWEEN COPPER LEAD AND TIN PLATING

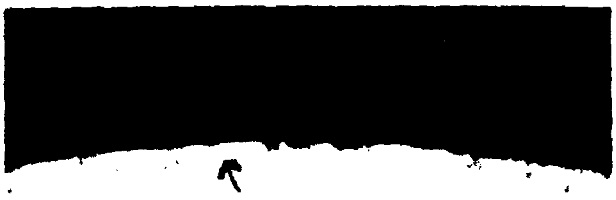


Figure 5 - ELECTRON MICROPROBE. ANALYSIS IDENTIFYING INTERMETALLIC

Figure 6 - SOLDERABILITY TEST FAILURE

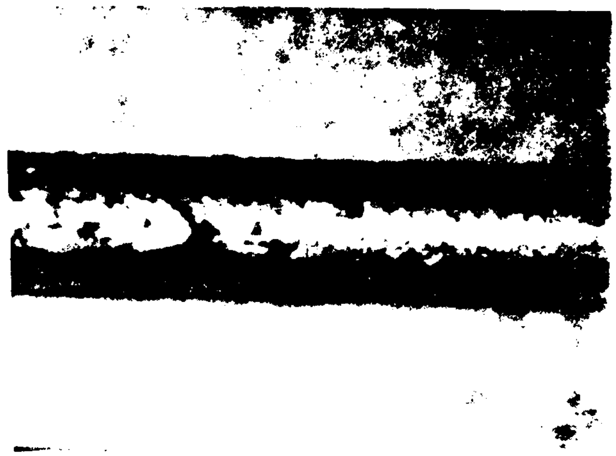


Figure 7 - TIN PLATING DAMAGED BY ORGANICS

Figure 8 - TIN PLATING DIRECTLY ON NICKEL-IRON ALLOY

Figure 9 - POOR SOLDERABILITY OF TIN PLATING WITH NO BARRIER PLATE

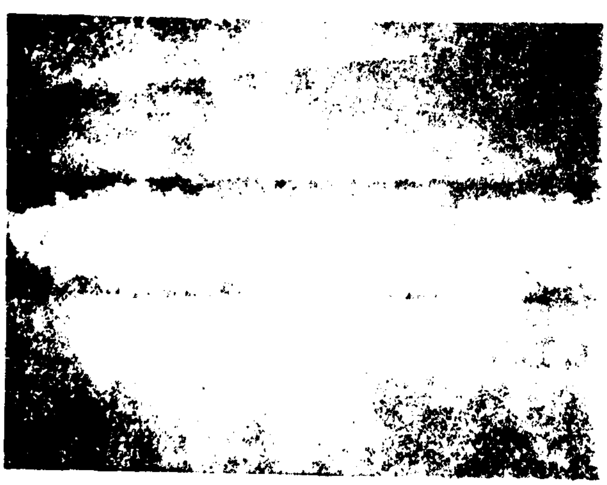


Figure 10 - DEWETTING

Figure 11 - NONWETTING

Figure 12 - PINHOLES

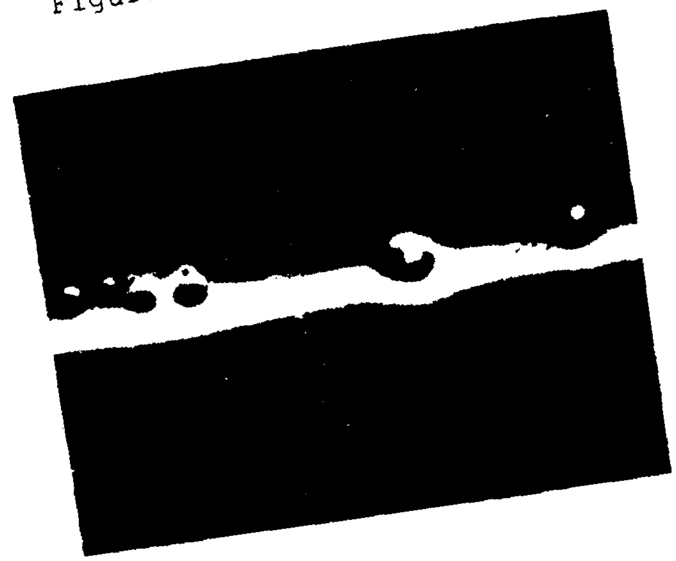


Figure 13 - POROSITY

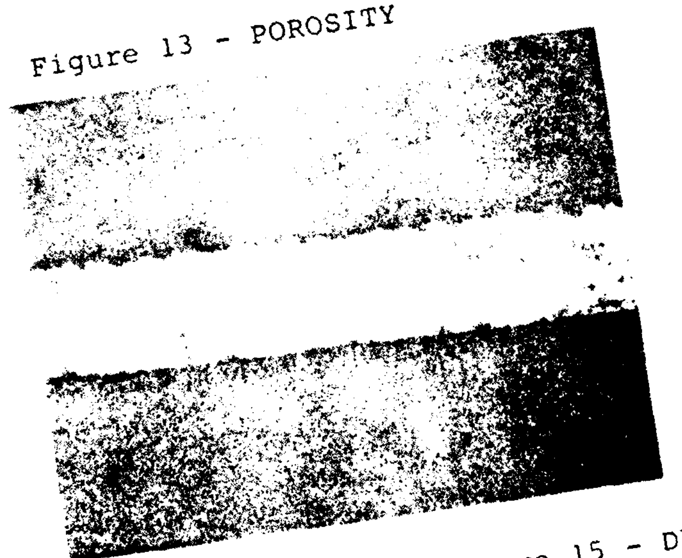
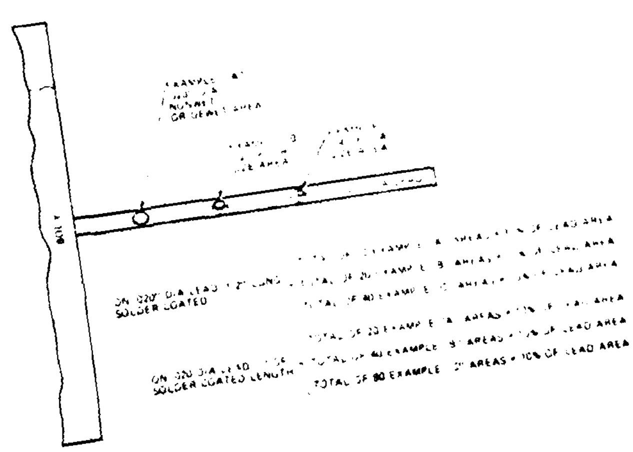


Figure 14 - FOREIGN MATERIAL

Figure 15 - DEFECT AREAS AS PERCENTAGE OF CYLINDRICAL SURFACE AREA



ANALYSIS OF SOLDER JOINT INSPECTION AND REWORK METHODS

by

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January 1983

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Introduction

One of the perpetual concerns in any electronic manufacturing facility is the inspection and rework of solder joints in a printed wiring board assembly. Rework is more often known as touch-up. This activity is time-consuming, labor-intensive and therefore costly. The other major concern to a manufacturing facility is the effect on reliability which the inspection and rework operation contributes. In today's marketplace, the reliability of electronic hardware is often the most important concern. The reliability not only impacts MTBF but has extensive cost impact.

Once the various impacts of the inspection and rework (touch-up) operations are realized the question becomes, "what is the best way to go?" This "best way" must be the most effective, least damaging and least costly way. Previously, this was a difficult decision to reach due to the number of variables. The second part of this paper describes a means of objectively designing an inspection/rework scheme which will be the most effective for a particular manufacturing operation.

Reliability Impacts

The best solder joint is the first solder joint. The reason for this is partly metallurgical. The more times a joint structure is submitted to soldering heat the thicker the intermetallic compound, formed between the solder and the base metal, becomes. The optimum thickness for this intermetallic is 1 µm or a little less. The thicker it becomes, the more brittle the joint will be to certain types of stresses. Typically those that come from mechanical shock or lead bending. Fatigue and creep are not generally affected by the thicker intermetallic.

A second reason that repeated exposures to soldering heat is degrading is the effects on the PWB laminate structure. It has been shown that these thermal exposures will result in increased failures in multilayer board structures due to effects on the plated through hole (barrel and interconnect cracking, etc.). Also effects on foil adhesion (lifted runs, etc.) and insulation resistance (charring, etc.) are seen.

A third reason for limiting the number of soldering applications is the possibility of covering up a serious defect by piling on the solder. Fortunately, this is easy to control by proper procedures. This will be discussed later in this paper.

Based on the above, it can be seen that the minimizing of soldering applications can improve the reliability of printed wiring assemblies. As a secondary effect costs will also be reduced. Every operation performed to correct a bad solder joint adds cost. This can be as high as a factor of 100-200 over the original joint cost if a field failure occurs. If the rework results in scrap then the cost can even be higher. Analysis can show that the addition of dollars at the front end to insure a good joint the first time will be cheaper than rework. The authors hope to show this in the remainder of this paper.

Inspection

To be effective, the inspection of solder joints must meet the following criteria:

1) Defects must be located

2) Must be able to distinguish between functional and cosmetic defects

3) Must be cost-effective

4) Must be efficient

It can be seen that to satisfy all of the criteria, the inspection system used in practice must be a compromise. Excessive scanning time cannot be tolerated but it must be long enough to detect defects. A maximum of functional defects must be found with a minimum of cosmetic defects included. This requires good training and good visual and written standards to inspect to. The typical tendency of an inspector is to get more and more critical requiring longer scan times and the citing of more joints which are "bad". Analysis of this shows the inclusion of more minor cosmetic problems in the "bad joint" calls.

As stated, good inspection requires good training. It also requires periodic recalibration to the criteria. This can be either formal or informal. In some cases, we have found it effective to employ daily informal recalibration with monthly to trimonthly formal recalibration. The daily procedure is to review all the standards at the beginning of the shift. This requires that each person doing inspection must have these standards at the work station and not in a file drawer in the office. The periodic formal sessions should only take an hour or so and should be handled by QC. It also gives a chance to discuss problems and be updated on anything new.

Tools

The tools of rework are usually hand-soldering and de-soldering tools. For effective rework, these should be temperature controlled and properly maintained. The importance here is the PWA being worked on be subjected to the mildest treatment possible in terms of temperature, time and number of cycles.

A soldering or de-soldering tool must be able to satisfy the metallurgical demands of soldering without causing damage. Generally, this means heating the joint area to 450-500°F within 1-2 sections. On heavy multilayer boards, this may mean a gentle preheating is required.

In order for a tool to meet the above requirements, it must be properly tinned for maximum heat transfer. This means good maintenance. Improperly maintained tools are one of the main causes of damage and scrap.

Temperature controlled tools are usually best as they are capable of supplying sufficient heat without having to be run at excessively high temperatures. The tip temperature should be set so that the metallurgical criteria are met without damage. The actual tip temperature is secondary. As long as it can be accurately and repeatably set or reset is the prime consideration. Joint temperature is the primary factor.

Rework (Touch-up)

Rework to be an effective procedure must:

1) Correct what it is supported to correct

2) Improve reliability

3) Not cause damage

4) Be cost-effective.

In order to satisfy these demands, proper procedures must be used, effective flow paths must be employed and a means of reducing the amount of rework performed. Also rework must not be a dead-end street. Rework is a procedure for correcting an original deficiency in the system. Therefore a means of reducing deficiencies and improving the system must also be employed.

Typically, the rework system found in most manufacturing facilities today is a variation of that shown in Figure 1. After PWAs exit the wave soldering (or other automated soldering process), the assembly does to a touch-up operator. This operator is often a low rate person very susceptible to union bumping procedures. The training received may be by a predecessor, a peer or the foreman. In a "high reliability" house, the person may have a higher rating and be professionally trained.

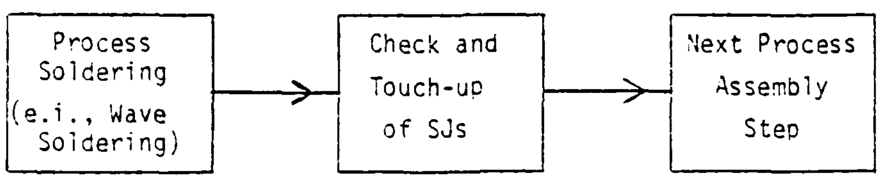


Figure 1. Often Found Inspection and Touch-up System.

The purpose of this person is to look at the solder joints (inspection) and fix up what needs to be fixed (rework). The typical result is to "correct" solder joints which really need no correction. "Gee, the one I just hit is brighter and shinier than the rest! I better fix them too." Unfortunately, this happens all too often. It is the result of improper training and/or standards to work to. In one plant, we have found a 500% overkill rate on touched up joints.

Another aspect of the "typical" system is that as the rework is done on each board, it is passed on to the next operation and another one is started. The only record kept may be the number of times it is reworked. Lost is the data showing where the defect was, what type it is and how many times has it occurred there. This aspect will be discussed in detail in the remainder of this paper.

When confronted with what appears to be exorbitant amounts of post process rework, a cost minded manager is likely to find himself in want of "quality" data from which to commence effective statistical problem analysis. More likely, and generally as a result of follow-on "fire fighting" action plans, we often find that the only available information falls into two general categories"

1) Post-facto, manufacturing process audit data.

2) Well-intentioned, but parochial opinions from those directly involved prior, during, and after process events.

As we all are aware, such data base is highly vulnerable to the pitfalls associated with short term collection intervals. A usual consequence is ineffective solutions which arise through impatience and mixing of one's "trivial many" with the true "vital few" causes-to-effect scenario. End result can be a not so merry trip down the "yellow brick road."

A Better Mousetrap?

In recent years, there has been considerable activity to improve the solder joint inspection/rework areas in a manufacturing plant. The increased complexity of circuits and the increased potential for damage have been the motivation for change. Costs and reliability have been the drivers.

The needs that have been identified for the system are similar to those already noted with some additions. One of these is the need to make materials or process changes to prevent defects. Another is fast notification when process problems occur.

The usual and very logical response to the gathering of "solid", unbiased data, is the introduction of real time data collection schemes between everyday process procedures. Combined with an effective statistical feedback and quality control program, such information will eventually head to meaningful and effective problems management.

Based on the newer needs, a system such as outlined in Figure 2 has developed. The prime elements of the system are the separation of inspection and rework and the installation of feedback loops.

The separation of the inspection and rework or touch-up steps puts the quality function under the quality organization and the manufacturing function under the manufacturing organization. It also allows for specialists in the two functions to be employed and reduces the tendency for overkill in the touch-up of joints. Based on experience, the cost impact of the separation tends to be no increase and many report a reduction in cost. The addition of a higher rate inspector is usually offset by a reduction in the number of rework personnel.

The separation of functions also opens the door for efficient data collection at the inspection station. The defect type, its location and how often the defect occurs is needed as a minimum. The data can be taken manually onto sheets for later compilation or it can be input directly into a computer terminal or a personal computer. Locations can be noted on a layout copy or by using component numbers. Defects can be categorized into as few as five types and can be assigned numbers.

Unfortunately, a most obvious objection to "in-process" data gathering schemes is their cost of implementation and maintenance. If already in place, but not utilized to potential, such programs become less than welcome and are usually the first of visible events to become "axed" when dealing with the pressures of schedules and/or belt-tightening efforts. A possible way to deal with this is to temper the "not so cost effective" stigma of data collections schemes by demonstrating that such programs can be integrated into manufacturing flow as an inherent part of desirable control mechanisms.

Once a defect has been found, it is then marked. Colored flux has been found to be an effective marking agent. The touch-up or rework operator then works only on those joints marked.

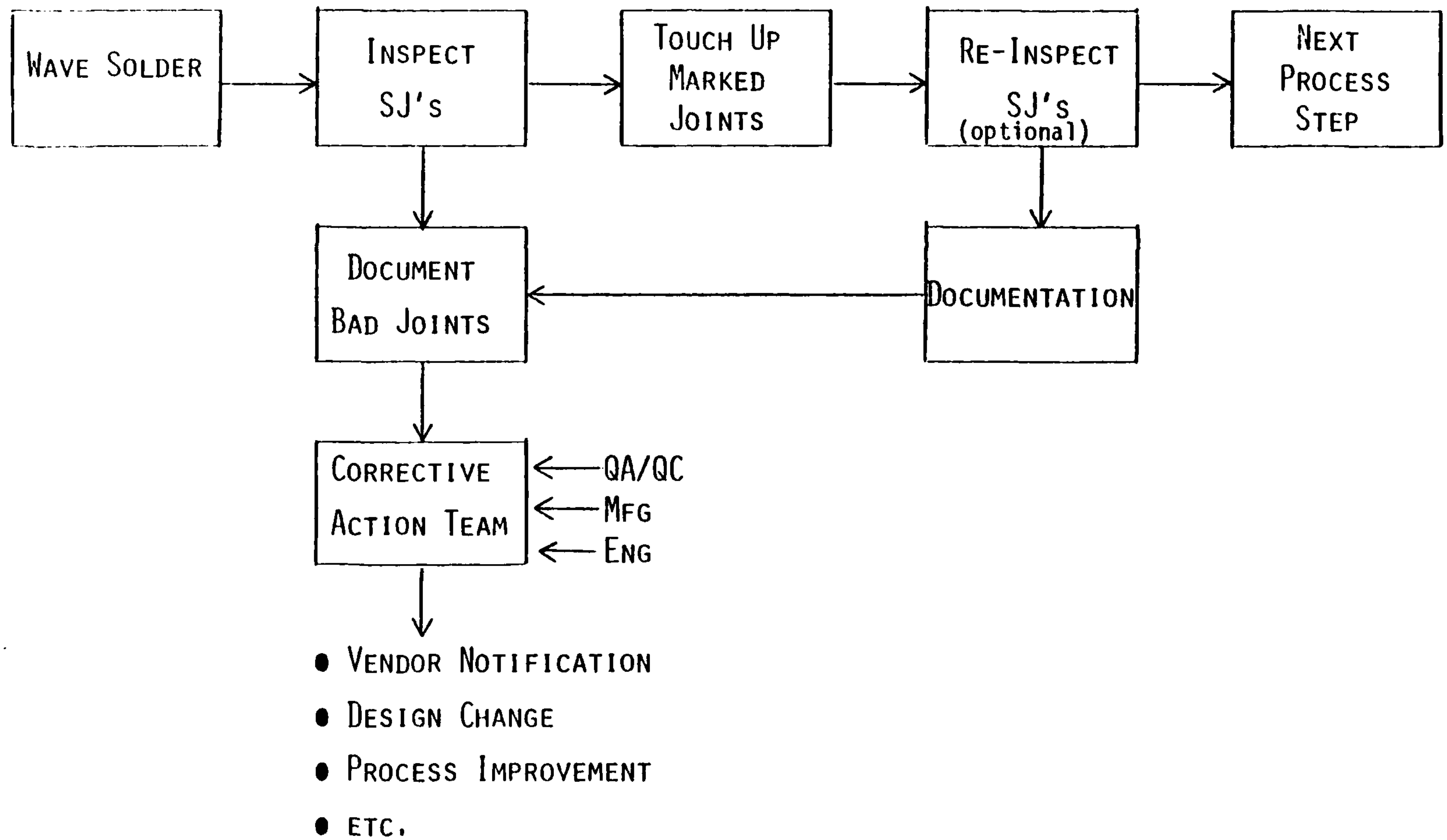
The data so collected forms the basis of the feedback loop. A key ingredient in the feedback loop is the corrective action team. This team, by the nature of its mission, needs to be manned by persons with the necessary authority. The team should not be large; 3 to 5 persons is optimum. It must contain representatives from the engineering, manufacturing and quality organizations.

The main source of information used by the team is the inspection reports. Added information from test areas and the field supplement the inspection data. Depending on the circumstances, the team may meet daily or even weekly. Periods longer than one week between meetings are ineffective in maintaining control of a process and its input materials.

Included in the corrective action team's inputs is a reporting back requirement after corrective actions have been instituted. This information coupled with the post-corrective action inspection reports show the improvement factor of the corrective action.

Figure 2

INSPECTION AND TOUCH-UP



The typical experience of installing an inspection/rework scheme such as has been described is an initial flood of problems and paperwork. However, as control is gained, the number of problems decrease and the volume of paperwork is drastically reduced. Touch-up rates per PWA are often reported in terms of reductions from 40 to 50% of the joints down to less than 1%.

Inspection/Rework Scheme Analysis

To determine whether or not the addition of a set of process steps will be worth the effort, intuitively we place ourselves aside real-world events and try to obtain a feeling for their impact given some sort of on-going or baseline situation. For a description to an orderly approach on this, we'll dub the process: Situation Model Simulation and Comparison (SMSC). Simply put, by reducing one's given manufacturing material flow to step elements, and then summing same into a modest mathematical analogy (model), some readily visible "what-if" insight can be realized and exercised through terms value variance. As can also be imaged, this model analysis approach is dramatically enhanced when derived algorithms are integrated into computer programs whereby the effects of process step element time changes can be readily examined.

The outline shown in Figure 2 has many variations which can affect cost and product flow. Using SMSC, one can analyze these variations and the optimum one can be selected for a particular manufacturing operation.

The example SMSC presented herein will focus on process flow associated with "in-mass" solder joint processing, defects identification and corrective action (i.e., Printed Circuit Assembly, post wave solder "check and touch-up").

Process verification scheme (Model I) proposes three variations (cyclic schemes) which envelop a data gathering effort. A simplified quantitative iteration of each is compared to a process scheme (Model II) which employs both defect corrective action and defect identification as a single process operation prior to any formal solder joint checks. On-going and highlighted during the development of each model algorithm are the apparent advantages and disadvantages of each mode. As we will see, these conclusions, when put into perspective with model curve analysis, can be very useful in vividly demonstrating that the most cost-effective approach may not necessarily be the one with fewer process steps or post process control. Such is the case where there exists opportunity for vast numbers of judgement calls leading to higher involvement and unnecessary "touch-up" (as is exemplified by a skewed Model II curve).

Manufacturing Process Flow Model Analysis

In order to effectively analyze a process flow model, it must be broken down into variables and step elements. The following listing shows these aas we have determined them for a typical process. Listed also are the definitions of the elements.

MODEL VARIABLES/STEP ELEMENTS: DEFINITIONS & ASSUMPTIONS

T_h; Time given to handle an entire Printed Circuit Board Assembly (PCA) between each station of a given model scheme. Batch or line mode processing can be assumed irrelevant as long as consistency of transfer method is maintaine dor a given PCA. Measurement = seconds/PCA.

T_{im}; Seconds required to judge, mark and document the location of an unacceptable solder joint on a given PCA undergoing solder joint inspection.

T_c; Time to clean an entire PCA once corrective action on all unacceptable solder joints has been completed. Measurements = seconds/PCA.

N_j; Number of solder joints per given PCA type.

U_j; Ratio of unacceptable solder joints per given PCA type to the total number, N_j. Some typical unacceptable solder joint (defect) classifications, could be:

(a) Blow holes or voids
(b) Dewetted surface †
(c) Solder bridge (projection)
(d) Solder icicle(s)
(e) Mechanical configuration discrepancy
(f) Unsoldered joint/insufficient wetting
(g) Too much solder (wetting profiles hidden)

† = Usually non-correctable by line operator intervention.

'U_j' assumed to generally be a function of:

(a) Automated/semi auto process conditions
(b) Solder joint designs (per given PCA)
(c) Component lead and PCA run/track "wetability"
(d) Pre-process PCA preparations

'U_j' identification errors are assumed to be small for certified inspectors and operators. Factors involving (1)* (1-Px) will, therefore, be assumed equal to '1'. Check errors in the identification of U_j are a side issue to model analization and will be examined in terms of model advantages/disadvantages. Events are independent.

*Reference

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T_s; Average time to scan a single solder joint (per given PCA type) by a certified checker/inspector. Measurement = seconds/solder joint.

P_i; Probability of error in inspection leading to unacceptable solder joints being passed through the inspection (check) station. P_i is a value characteristic of a given inspector (checker) based on measured performance. (Value between 0 and 1.)

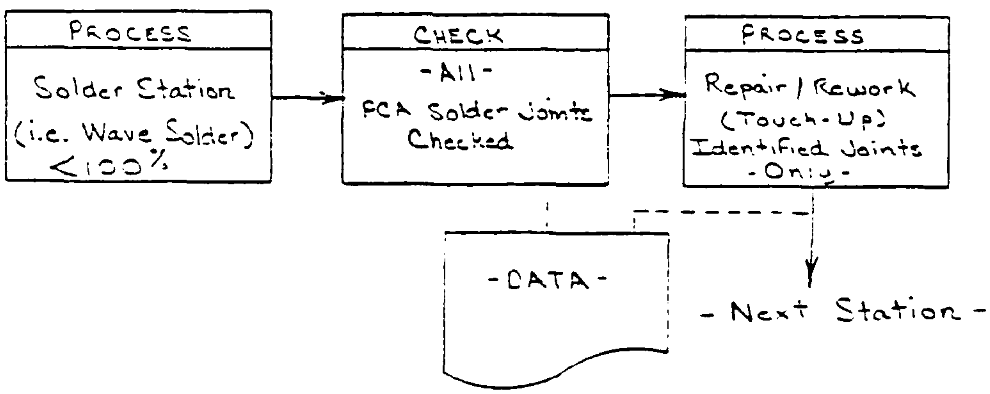
P_c; Probability of error expected during corrective "touch-up" action whereby unacceptable solder joints destined to be corrected remain unacceptable. (Value between 0 and 1.)

T_r; Average time required to effect corrective rework on a single solder joint previously identified as being unacceptable. Measure = seconds/solder joint.

Model Analysis

A. Model I, Scheme 1

The first model chosen to evaluate is a variation of that shown in Figure 2. Once the process is determined, variables and step elements can be assigned and a mathematical equation developed to model the process. The process of modelling is shown as follows:



(1) Check Station receives PCA from "Automated" Process Station = T_h

(2) Checker scans all PCA solder joints = $T_s \cdot N_j$

(3) Checker marks unacceptable solder joints = $T_{im} \cdot U_j \cdot N_j$ (1)Ref.

(4) PCA transferred to Touch-up Station = T_h

(5) Touch-up Station receives PCA from Check Station = T_h

(6) Corrective touch-up effected on all PCA joints previously identified unacceptable = $T_r \cdot U_j \cdot N_j$ $(1)_{Ref.}$

(7) PCA cleaned = T_c

(8) PCA transferred on to next station = T_h

(A.1) Total time equation for above Scheme:

$$4T_h + T_c + N_j \cdot \quad T_s + U_j\ (T_{im} + T_r)$$

(A.2) Probable # of unacceptable joints missed this Scheme:

$$N_m = P_i \cdot (U_j \cdot N_j) + P_c \cdot \quad (U_j - P_i \cdot U_j \cdot N_j) \quad \cdot N_j$$

As each scheme is modeled and evaluated, advantages and disadvantages of the scheme relative to other schemes within the basic model will become apparent. These are better thought of as strong and weak points rather than distinct advantages and disadvantages at this point in the analysis.

The strong and weak points for Model I, Scheme 1 are as follows:

Strong points this scheme:

Lowest cost:

(a) Highest PCA throughout
(b) Check proportion of total cycle time is minimum
(c) Touch-up operator burden small

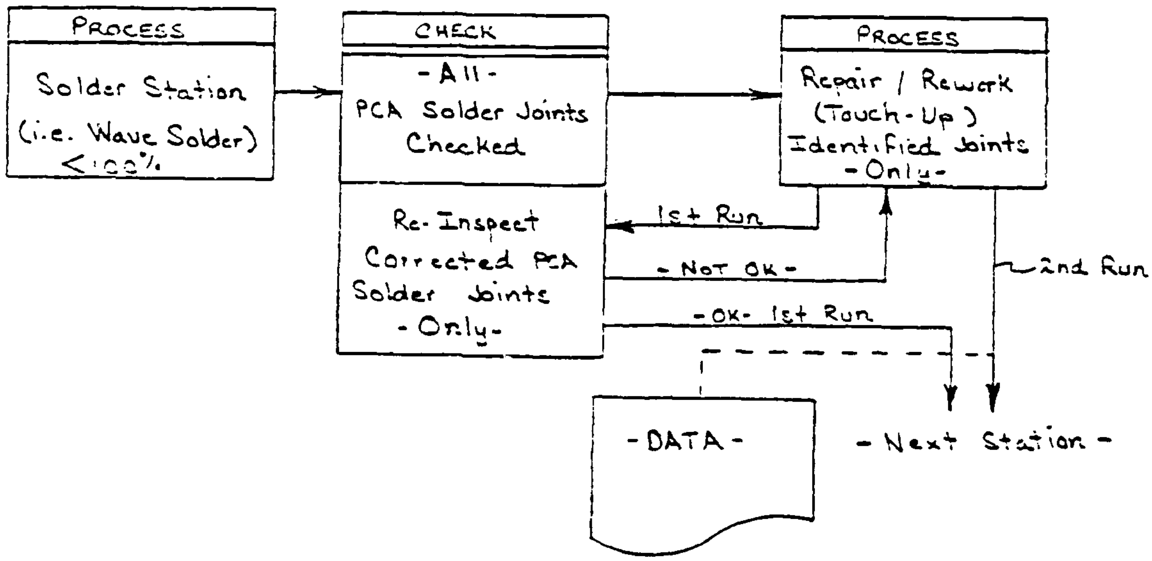
Weak points this scheme:

Greatest chance for unacceptable solder joints being missed and passed on:

(a) No positive assurance that any corrective action did indeed take place.
(b) Greatest probability that an unacceptable solder joint on a given PCA will be missed due to inherent error associated with both checker and "touch-up" operator.

B. Model I, Scheme 2

This is the second variation of the process shown in Figure 2. The analysis is as follows:



Steps 1-8 of Model I, Scheme 1 applicable -

(9) Check Station receives PCA from Touch-up Station = T_h

(10) Checker identifies rework solder joints from Touch-up paperwork $\cong T_{im} \cdot U_j \cdot N_j$ $(1)_{Ref.}$

(11) Checker scans reworked (touched up) joints = $T_s \cdot U_j \cdot N_j$ $(1)_{Ref.}$

"OK" Cycle:

(12) PCS transferred to next station = T_h

"Not OK" Cycle:

(12) Checker marks unacceptable solder joints = $T_{im} \cdot P_c \cdot U_j \cdot N_j$ $(1)_{Ref.}$

(13) PCA transferred to Touch-up Station = T_h

(14) Touch-up Station received PCA = T_h

(15) Touch-up Station effects corrective action to PCA solder joint(s) identified = $T_r \cdot P_c \cdot U_j \cdot N_j$ $(1)_{Ref.}$

(16) PCA cleaned = T_c

(17) PCA transferred to next station = T_h

(B.1) Total time equation for above Scheme:

"OK" Cycle: $6T_h + T_c + N_j \cdot \left[T_s + U_j \cdot (2T_{im} + T_r + T_s)\right]$

"Not OK" Cycle:

$$8T_h + 2T_c + N_j \cdot \left[T_s + U_j\ (2T_{im} + T_r + T_s + P_c \cdot T_r + P_c \cdot T_{im})\right]$$

(B.2) Probable # of unacceptable joints missed this Scheme:

"OK" Cycle: $N_m = P_i \cdot (U_j \cdot N_j) + P_i \cdot (P_c \cdot U_j \cdot N_j)$

"Not OK" Cycle: $N_m =$ "OK" Cycle $+ \cancel{P_i \cdot P_c \cdot (P_c \cdot U_j \cdot N_j)} \rightarrow \emptyset$

The strong and weak points of this scheme compared to others within the basic model are as follows:

<u>Strong points this scheme</u>:

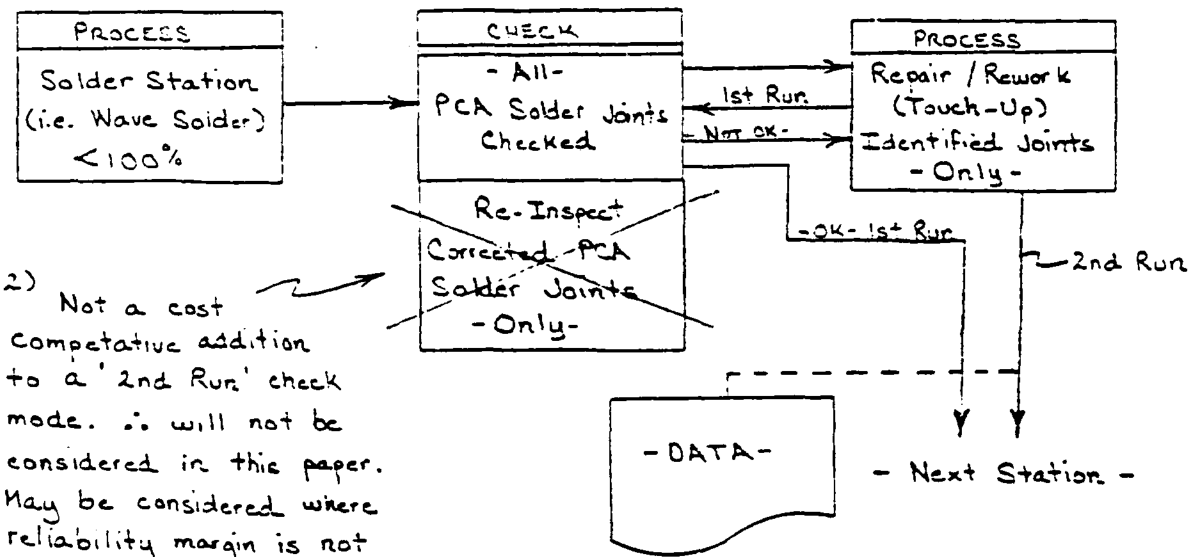
Medium range cost scheme and fair degree of positive assurance on corrective action.

<u>Weak points this scheme</u>:

Only a small increase in probability of catching an unacceptable solder joint condition before passing PCA.

C. Model I, Scheme 3

The last scheme in this basic model is as follows:



(2) Not a cost competative addition to a '2nd Run' check mode. ∴ will not be considered in this paper. May be considered where reliability margin is not felt to be adequate.

Steps 1-8 of Model I, Scheme 1 applicable -

(9) Checker Station receives PCA from Touch-up = T_h

(10) Checker scans all PCA from Touch-up = $T_s \cdot N_j$

"OK" Cycle:

(11) PCA transferred to next station = T_h

"Not OK" Cycle:

(11) Checker marks unacceptable joints = $T_{im} \cdot (U_j \cdot P_i) \cdot N_j$ $(1)_{Ref.}$

(12) PCA transferred to Touch-up Station = T_h

(13) Touch-up Station receives PCA from Check Station = T_h

(14) Corrective touch-up effected on all PCA joints previously identified unacceptable = $T_r \cdot (U_j \cdot P_i) \cdot N_j$ $(1)_{Ref.}$

(15) PCA cleaned - T_c

(16) PCA transferred to next station = T_h

(C.1) Total time equation for above Scheme (not OK):

$$8T_h + 2T_c + N_j \cdot \left[2T_s + U_j \cdot (T_{im} + T_r + P_i \cdot T_{im} + P_i \cdot T_r)\right]$$

(C.2) Possible # of unacceptable joints missed this Scheme:

$$N_m = P_i \cdot (P_i \cdot U_j \cdot N_j) + P_c \cdot \left[(P_i \cdot U_j - P_i{}^2 \cdot U_j \cdot N_j) \cdot N_j\right]$$

The strong and weak points of this scheme are:

Strong points:

Greatest chance of catching unacceptable (post process) solder joints before passing PCA.

Weak points:

Highest cost:

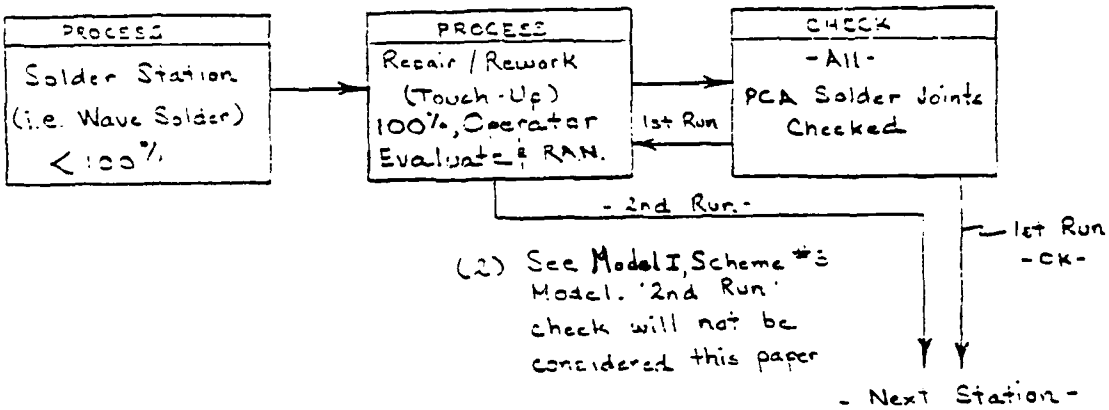
(a) Lowest PCA throughout rate
(b) Checker proportion of total cycle time, high

A side observation -

Some tendency may exist for a checker to not thoroughly inspect all PCA solder joints on the second passthrough. This could heavily impact the level of output quality should the checker not be impressed with the importance of a thorough examination even though the PCA is being passed through the Check Station for a second 100% check.

D. Model II

The schemes presented under Model I were all variation of what could be called the better way. In order to determine if it is really a better way than the "old" way must also be modeled. The following is the model for an average "Hi-Rel" manufacturing environment. This will be called Model II. The analysis is as follows:



(1) Touch-up Station receives PCA from Automated Process Station = T_h

(2) Touch-up Station operator scans all PCA solder points - $T_s \cdot N_j$

(3) Touch-up Station operator identifies and makes judgement on joints needing corrective touch-up = $(1)_{Ref.}$ $T_{im} \cdot U_j \cdot N_j$ /3 (T_{oj} =1/3 T_{im}, no documentation required)

(4) Touch-up Station operator effects corrective action on joints needing same = $T_r \cdot U_j \cdot N_j$ $(1)_{Ref.}$

(5) PCA cleaned = T_c

(6) PCA transferred to Check Station = T_h

(7) PCA received by Check Station = T_h

(8) Checker scans <u>all</u> PCA solder joints = $T_s \cdot N_j$

"OK" Cycle:

(9) PCA transferred to next station = T_h

"Not OK" Cycle:

(9) Checker marks unacceptable solder joints = $T_{im} \cdot (U_j \cdot P_c) \cdot N_j$ $(1)_{Ref.}$

(10) PCA transferred to Touch-up Station = T_h

(11) Touch-up Station receives PCA from Check Station = T_h

(12) Corrective touch-up effected on all PCA joints previously identified unacceptable = $T_r \cdot (U_j \cdot P_c) \cdot N_j$ $(1)_{Ref.}$

(13) PCA cleaned = T_c

(14) PCA transferred on to next station = T_h

(D.1) Total time equation for above Scheme:

"OK" Cycle:

$$4T_h + T_c + N_j \cdot \left[2T_s + U_j \cdot (1/3\ T_{im} + T_r)\right]$$

"Not OK" Cycle:

$$6T_h + 2T_c + N_j \cdot \left[2T_s + U_j \cdot (1/3\ T_{im} + T_r + P_c \cdot T_r + P_c \cdot T_{im})\right]$$

(D.2) Possible # of unacceptable joints missed this model:

$$* \ P_m = P_c \cdot P_i \cdot U_j \cdot N_j + P_c \cdot \left[(P_c \cdot U_j - P_c \cdot P_i \cdot U_j \cdot N_j) \cdot N_j\right]$$

* If $P_i \approx P_c$, (where both operator and inspection have been similarly certified) then Model II rivals a Model I Cycle #3 for probable # of unacceptable joints missed.

Once the models have been completed and the analysis done, it is possible to determine the advantage of one model over another. In the case of Model I vs. II, we find that Model I has the following advantages:

1. Routing schemes for Model I, inherently, can be *efficiently designed to supply raw data/documentation on unacceptable solder joints as obtained directly off an automated, semi-automated, process station. Since evidence is destroyed with corrective action, obtaining similar data base through "Touch-up" Station operations, as with Model II, could prove very inconsistent. An example to this is when Model II sourcing becomes significantly influenced by stimulus arising from checker-to-operator impasse, etc. This leads us into observation 2.

2. A common argument of "touch-up" operators is: "that if in doubt, touch-it-up." This attitude reflects attempts to minimize embarrassments arising from unpleasant incidents of inspector (checker) judgement calls on soldering workmanship. By shifting a larger burden of final judgement calls to Q.C. checkers, this argument tends to be thwarted as being a driving force behind unnecessary "touch-up."

3. "Quality Level" output should become more consistent since final acceptability criteria associated witheach PCA is isolated to a set of independent event checks, versus random soldering "touch-up" assignments plus inspector (checker) judgement calls.

* Model I introduces a mode for smooth T_s (Tine-to-Scan) event flow.

Detailed Analysis of Models, Resultant Time Equations

Simplification procedures:

A. Time related variables consolidation:

(1) Let $T_c \approx 2T_h$ where T_h typically can range from 10-15 seconds/PCA.

(2) Let T_s = 4-5 seconds/solder joint

- assuming trained operators and inspections, also then let: $T_{im} - 5T_s$ & $T_r = 6T_s$

B. Error relationships consolidation:

Assuming both operators and inspections have been similarly trained/certified: $P_i = P_c$

For the analogies to follow, let us also assume that P_i or $P_c \approx .04$ (96% probability of catching an error)

Substituting these relationships back into the model time equations yields the following:

Model I:

Scheme #1:	$6T_h + N_j \cdot T_s \cdot (1 + 11U_j) = T_t$
Scheme #2 OK:	$8T_h + N_j \cdot T_s \cdot (1 + 17U_j) = T_t$
Scheme #2 Not OK:	$12T_h + N_j \cdot T_s \cdot (1 + 17.44U_j) = T_t$
Scheme #3 OK:	$10T_h + N_j \cdot T_s \cdot (2 + 11U_j) = T_t$
Scheme #3 Not OK:	$12T_h + N_j \cdot T_s \cdot (2 + 11.44U_j) = T_t$

Model II:

"OK" Cycle:	$6T_h + N_j \cdot T_s \cdot (2 + 7.7U_j) = T_t$
"Not OK" Cycle:	$10T_h + N_j \cdot T_s \cdot (2 + 8.1U_j) = T_t$

C. All equations are noted to have the general form: $B + N_j \cdot M = X$. This form, rearranged with N_j becoming the dependent variable, yields:

$N_j = \frac{X-B}{M}$; which is recognized as being ≡ MX + B; the general equation for a linear curve, slope intercept form.

i.e., for Model I, Scheme #4 "Not OK":

$$M = \frac{1}{T_s\ (2 + 11.44U_j)} \quad \& \ B + \frac{-\ 12T_h}{T_s\ (2 + 11.44U_j)}$$

This final version can become a useful tool for deriving quick/generalized relationships between models; Total Time (T_t) vs. number of joints/PCA. (See Graph Figure 3)

D. Performing a similar rearrangement of terms, making U_j the dependent variable, yields:

$U_j = \frac{X-B}{M}$; we now have the convenient forms for deriving quick comparison relationships between models for Total Time vs. Touch-up rate, i.e., for Model I, Scheme #3 "Not OK":

$$M = \frac{1}{(12T_h + N_jT_s)(11.44)} \quad \& \ B = \frac{-12}{11.44}$$

(See Graph Figure 4)

Summary Observations:

Considering "throughput" quality, control possibilities, and data accumulation possibilities which could lead to further "throughput" improvements, Model I Scheme #3 becomes very attractive. For a small and very predictable proportionate cost increase per PCA, cyclic and unpredictable rework costs, which tend to overshadow such fixed costs, are offset through controls inherently offered as part of an immediate post process check operation.

Time/Cost Burden Shift to Quality Control Check Operations:

Steps:

(1) Remove variable elements (per given Scheme) associated with check operations and derive a new general equation made up of Inspection/Check Station associated terms only.

FIGURE 3

TIME COMPARISON DIAGRAM FOR MODELIZED ROUTING SCHEMES (FIGURE 1.)

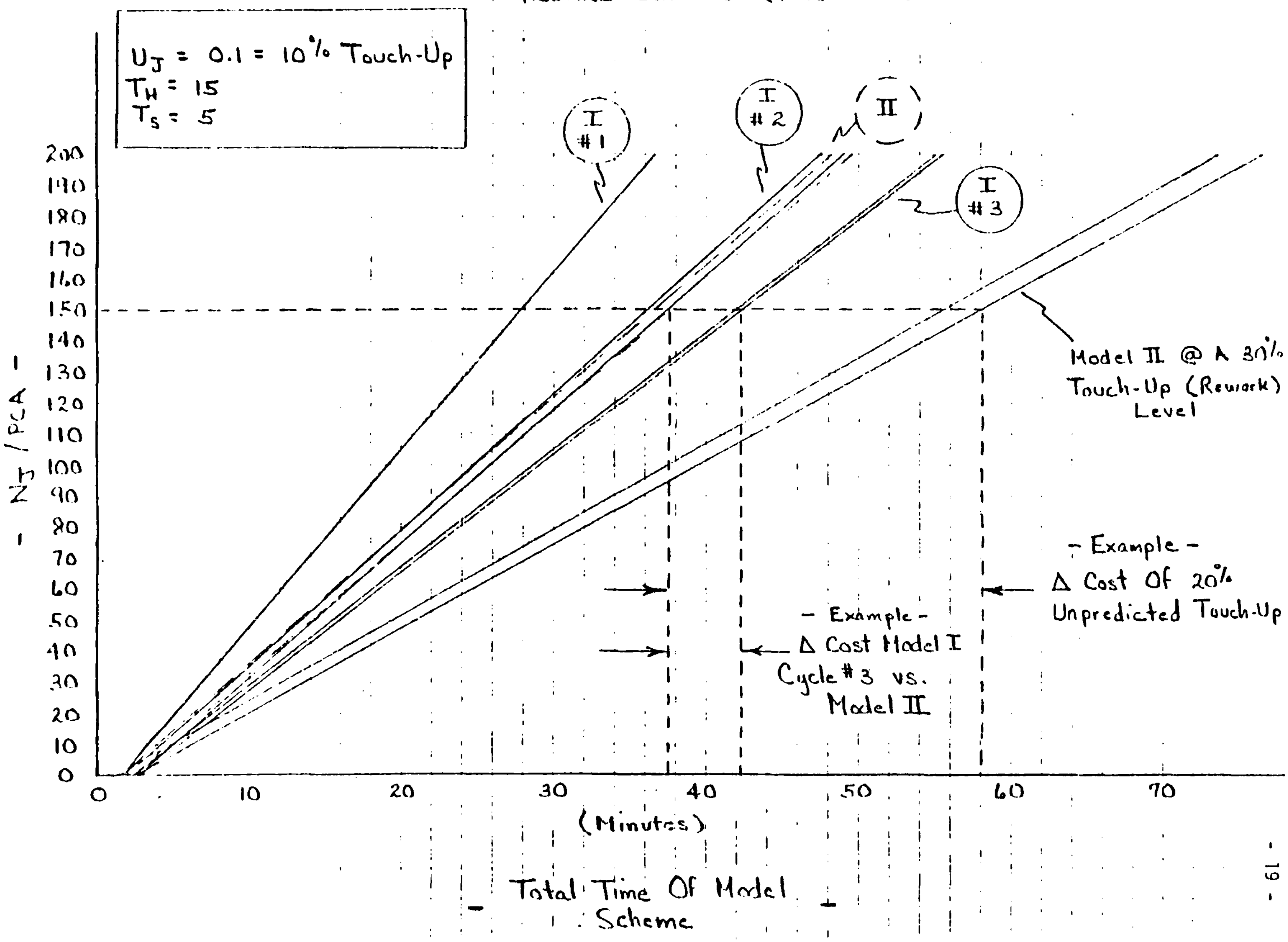
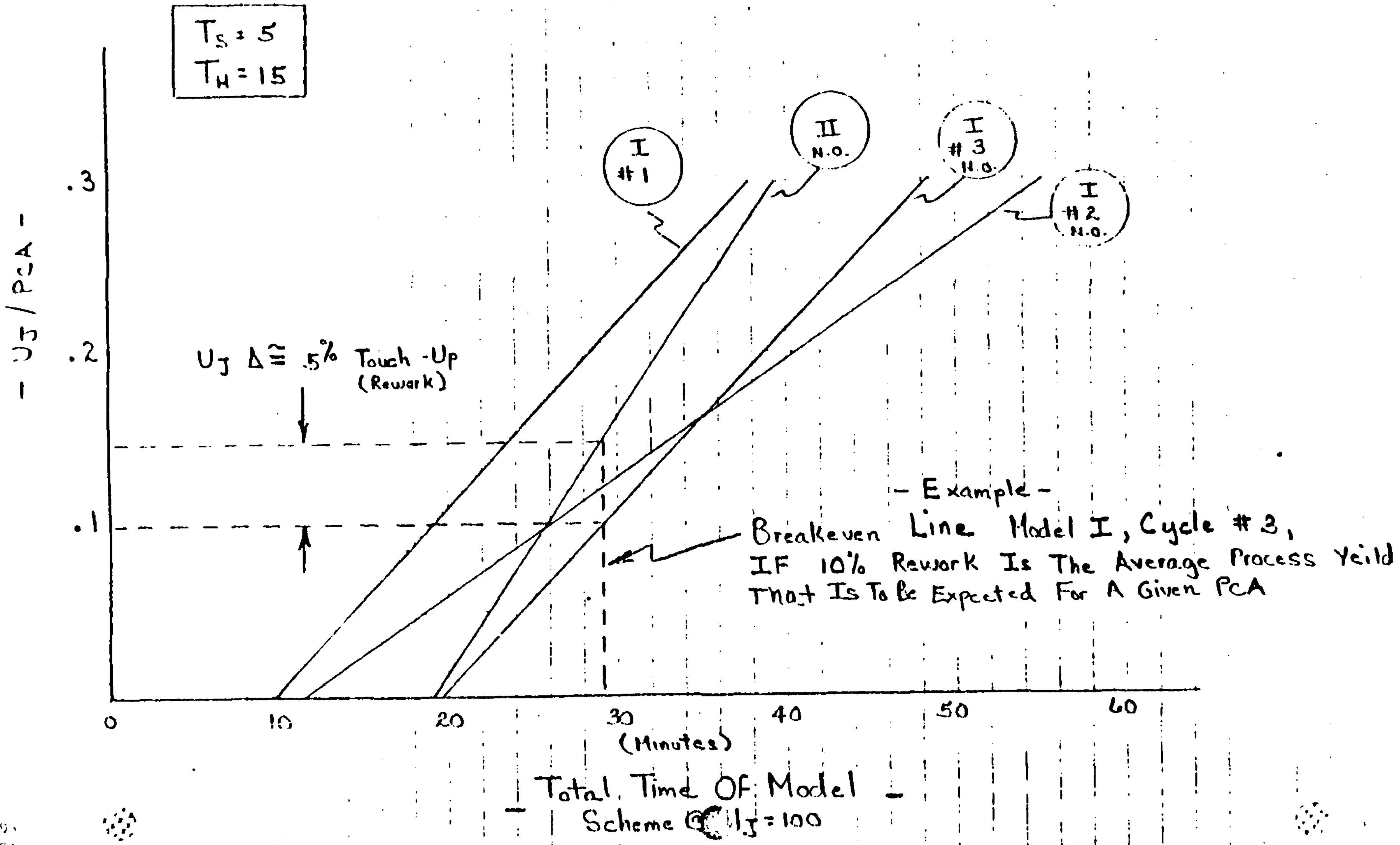


FIGURE 4

TIME COMPARISON DIAGRAM FOR MODELIZED ROUTING SCHEMES (FIGURE 2.)



(2) Substitute above equation via the following to find % total time burden rate for joint inspection/checks:

$$\frac{\dfrac{A \cdot T_h + N_j \cdot T_s \cdot (B + CU_j)}{60}}{\text{Total time of model scheme (minutes)}} \quad X\ 100$$

Example quality control burden prediction:

$N_j = 96$

Model I, Scheme #3, vs. Model II ("Not OK"):

$T_h = 15 \quad ; \quad P_i = .04$

$T_s = 15 \quad ; \quad P_c = .04$

$U_j = 7.6\%$ expected (as per process set-up study)

(a) <u>Scheme #3, Model I</u>

Total cycle time $= 12T_h + N_j \cdot T_s \cdot (2 + 11.44U_j) \quad /60$

$= 180 + 480\ (2 + 0.86944) \quad /60 \quad = \underline{25.95 \text{ minutes}}$

(b) <u>Model II</u>:

Total cycle time $= 10T_h + N_j \cdot T_s \cdot (2 + 8.1U_j) \quad /60$

$= 150 + 480\ (2 + 0.6156) \quad /60 \quad = \underline{23.42 \text{ minutes}}$

(c) <u>Model I, Scheme #3</u> ("Not OK") Inspection Station Associated Time Equation:

$$\frac{4T_h + N_j \cdot T_s \cdot (2 + 5.2U_j)}{60} = \frac{60 + 480\ (2.3952)}{60} = \underline{20.16 \text{ minutes}}$$

(d) <u>Model II</u> ("Not OK") Inspection Station Associated Time Equation:

$$\frac{2T_h + T_s \cdot N_j \cdot (1 + 0.2U_j)}{60} = \frac{30 + 480\ (1.0152)}{60} = \underline{8.62 \text{ minutes}}$$

Results:

Model I Scheme #3 Burden = $\frac{20.16}{25.95}$ X 100 = 77.69%

Model II Burden = $\frac{8.62}{23.42}$ X 100 = 36.8%

This shows the shift of the burden to quality control, where quality decisions should be, using Model I, Scheme #3.

Summary and Conclusions

1. In order to otpimize the inspection and rework areas in manufacturing facility, it is necessary to fully understand variables and step elements of the process including the cost and reliability impact of each.

2. Once the variables and step elements are known and understood, it is possible to develop mathemetical expressions to analyze a variety of inspection and rework process schemes.

3. An analysis of inspection and rework schemes will point the way to the optimum process for a manfacturing facility.

4. It is most often found that the optimum inspection and rework process will call for a separation of the two major functions. These are generally less costly, more effective and will reduce the amount of rework done.

5. A separated inspection and rework process combined with good data collection and a corrective action feedback loop provides for on-going process improvement and overall reductions in cost with increased hardware reliability.

APPENDIX A

Computer Analysis

Once a model is arrived at, it is possible to adopt it for input into a computer. This allows rapdi evaluation for several models for comparison.

First, it is necessary to refine the total time equations* to make them more easily programmed. The following are examples of refinement for Model I, Scheme 3 and Model II which were used in the main body of this paper.

Model I, Scheme #3

(a) $$T_t = 8T_h + 2T_s \cdot Nj + 2T_c + U_j \cdot N_j \cdot (1 - P_i) \cdot \Big\{T_r + T_{im} + T_{im} \cdot \big[P_i + P_c \cdot (1 - P_i)\big] + T_r \big[P_i + P_c(1 - P_i)\big]\Big\}$$

(b) $$U_j = (T_t = 8T_h - 2T_s \cdot N_j - 2T_c)/N_j \cdot (1 - P_i) \cdot \Big\{T_r + T_{im} + T_{im} \cdot \big[P_i + P_c \cdot (1 - P_i)\big] + T_r \big[P_i + P_c \cdot (1 - P_i)\big]\Big\}$$

+ (c) $$T_{Ti} = 4T_h + 2T_s \cdot N_j + U_j \cdot N_j \cdot (1 - P_i) \cdot \big[T_{im} \cdot (1 - P_i) + T_{im} + P_i + T_{im} \cdot P_c \cdot (1 - P_i)\big]$$

Model II:

(a) $$T_t = 6T_h + 2T_s \cdot N_j + 2T_c + U_j \cdot \big[N_j \cdot (1 - P_c) \cdot (T_{oj} + T_r) + N_j \cdot (1 - P_i) \cdot (T_{im} \cdot P_c + T_r \cdot P_c)\big]$$

(b) $$U_j = T_t - 6T_h - 2T_s \cdot N_j - 2T_c / \big[N_j \cdot (1 - P_c) \cdot (T_{cj} + T_r) + N_j \cdot (1 - P_i) \cdot (T_{im} \cdot P_c + T_r \cdot P_c)\big]$$

+ (c) $$T_{Ti} = 2T_h + T_s \cdot N_j + T_{im} \cdot U_j \cdot P_c \cdot N_j \cdot (1 - P_i)$$

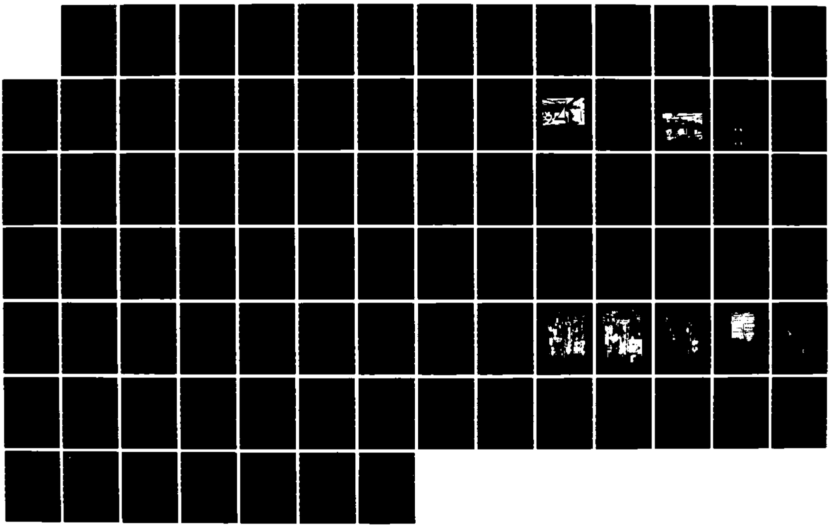
+ Total time associated with check/inspection events.

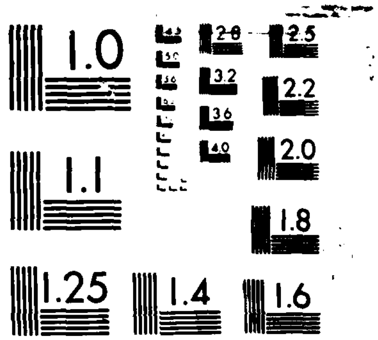
* More precise accounting of independent event error tendency.

After the refinements are made in the equations, the computer program can be developed. The following listing was developed for a TRS-80 pocket computer with extended basic (Level II) language and a graphics printer. Graph sets A and B are examples of the programs used.

AD-A168 243 SOLDERING TECHNOLOGY AND PRODUCT ASSURANCE (7TH) 4/4
PROCEEDINGS OF ANNUAL SE..(U) NAVAL WEAPONS CENTER
CHINA LAKE CA FEB 83 SBI-AD-E900 565

UNCLASSIFIED F/G 13/8 NL





MICROCOPY RESOLUTION TEST CHAR

```
10:PAUSE "SMSC,SO
   LDERING PROCES
   S"
15:RESTORE
20:NJ=0,T3=0,TT=0
   ,T2=0,U2=0,T13
   =0,T12=0,UJ=0,
   U3=0,Q1$="0
25:INPUT "# PCA S
   OLDER JOINTS="
   ;NJ
30:IF NJ<=1GOTO 1
   25
35:INPUT "% UNACC
   EPTABLE JOINTS
   =";UJ
40:IF UJ=0GOTO 55
41:UJ=UJ/100
45:IF UJ<0GOTO 12
   5
50:IF UJ>1GOTO 12
   5
52:GOTO 100
55:INPUT "SMSC TO
   TAL MODEL TIME
   =";TT
60:IF TT<=0GOTO 1
   25
61:TT=TT*60
65:INPUT "ENTER B
   ASELINE MODEL#
   :";N
70:IF N>2GOTO 125
75:IF N<1GOTO 125
80:IF N=2GOTO 95
85:T3=TT
90:GOTO 100
95:T2=TT
100:READ TH,TS,TC,
    TI,TR,TJ,P1,PC
105:IF TH*TS*TC*P1
    *PC*TI*TR*TJ<=
    0GOTO 150
110:IF PC>1GOTO 13
    5
115:IF P1>1GOTO 13
    5
120:GOTO 170
125:PRINT "INVALID
     #,REVIEW INPU
    T"
130:GOTO 15
135:PRINT "INVALID
     PROBABILITY V
    ALUE"
140:PRINT "REVIEW
    PROB. INPUT DA
    TA"
145:END
150:PRINT "INVALID
     DATA FIELD"
155:PRINT "REVIEW
    DATA FIELD"
160:END
170:IF T3<>0GOTO 1
    85
175:IF T2<>0GOTO 2
    00
180:GOTO 210
185:GOSUB 610
190:UJ=U3
195:GOTO 210
200:GOSUB 635
205:UJ=U2
210:GOSUB 600
220:GOSUB 620
225:GOSUB 630
230:GOSUB 645
235:X=(Q3/T3)*100
240:Y=(Q2/T2)*100
245:TD=ABS (T3-T2)
    /60
250:S2=T2,T2=T3
255:GOSUB 635
260:PD=(UJ-U2)*100
261:T2=S2
265:BEEP 1
266:GOSUB 635
267:GOSUB 610
268:PRINT "% UNACC
    .JOINTS,MODEL
    I="
269:PRINT U3*100
270:PRINT "% UNACC
    .JOINTS, MODEL
     II="
271:PRINT U2*100
272:PRINT "TOTAL T
    IME MODEL I="
273:PRINT T3/60
275:PRINT "TOTAL T
    IME MODEL II="
276:PRINT T2/60
280:PRINT "Q.C.CHE
    CK BURDEN,MODE
    L I="
281:PRINT X
285:PRINT "Q.C.CHE
    CK BURDEN,MODE
    LII="
286:PRINT Y
290:PRINT "MODELS
    TIME DIFFERENC
    E="
291:PRINT TD
295:PRINT "REWORK
    % DIFFERNCE="
296:PRINT PD
300:IF Q1$="Y"GOTO
    420
305:INPUT "WISH SI
    NGLE MODEL CHG
    .?":Q1$
310:IF Q1$<>"Y"
    GOTO 420
315:INPUT "ENTER C
    HG. MODEL#";N
320:IF N<=0GOTO 34
    0
325:IF N>=3GOTO 34
    0
330:IF N=1GOTO 350
335:IF N=2GOTO 380
340:PRINT "ILLEGAL
     MODEL #"
345:GOTO 315
350:INPUT "NEW % U
    NACC.PARAMETER
    =";UJ
355:IF UJ*100<=0
    GOTO 410
360:IF UJ*100>1
    GOTO 410
365:GOSUB 600
370:GOSUB 620
375:GOTO 235
380:INPUT "NEW % U
    NACC.PARAMETER
    =";UJ
381:UJ=UJ/100
385:IF UJ<=0GOTO 4
    10
390:IF UJ>1GOTO 41
    0
395:GOSUB 630
400:GOSUB 645
405:GOTO 235
410:PRINT "ILLEGAL
     % UNACC.ENTRY
    "
415:GOTO 315
420:INPUT "WISH GR
    APHICS DISPLAY
    ?";Q2$
425:IF Q2$="Y"GOTO
    435
430:IF Q2$<>"Y"
    GOTO 1000
435:U=NJ,G=190
436:GOSUB 950
439:S2=S
440:IF T3>T2GOTO 4
    55
445:V=T2
450:GOTO 460
455:V=T3
460:GOTO 800
600:C=(1-P1)*(TR+T
    I+TI*(P1+PC*(1
    -P1))+TR*(P1+P
    C*(1-P1)))
602:T3=8*TH+2*TS*N
    J+2*TC+UJ*NJ*C
605:RETURN
610:D=(1-P1)*(TR+T
    I+TI*(P1+PC*(1
    -P1))+TR*(P1+P
    C*(1-P1)))
612:U3=(T3-8*TH-2*
    TS*NJ-2*TC)/(N
    J*D)
613:IF U3<=0GOTO 5
    38
615:RETURN
```

```
620:C3=4*TH+2*TS*N
    J+UJ*NJ*(1-P1)
    *(T1*(1-P1)+T1
    *P1+T1*PC*(1-P
    1))
625:RETURN
630:T2=6*TH+2*TS*N
    J+2*TC+UJ*(NJ*
    (1-PC)*(TJ+TR)
    +NJ*(1-P1)*(T1
    *PC+TR*PC))
632:RETURN
635:U2=(T2-6*TH-2*
    TS*NJ-2*TC)/(N
    J*(1-PC)*(TJ+T
    R)+NJ*(1-P1)*(
    T1*PC+TR*PC))
636:IF U2<=0GOTO 6
    38
637:COTO 640
638:PRINT "ILLEGAL
     TIME ENTRY"
639:PRINT "RE-EVAL
    UATE INPUTS":
    GOTO 15
640:RETURN
645:02=2*TH+TS*NJ+
    T1*UJ*PC*NJ*(1
    -P1)
650:RETURN
700:DATA 10,4,20,1
    2,34,4.500,.02
    ,.02
800:GRAPH
805:GLCURSOR (0,0)
    :COLOR 6
810:GLCURSOR (18,0
    ):SORGN
815:LINE -(198,0)
820:GLCURSOR (0,0)
825.FOR C=0TO 190
    STEP 10
830:GLCURSOR (C,0)
835:LINE -(C,5)
840:GLCURSOR (C,65
    )
845:CSIZE 1
850:ROTATE 1
855:H=C*S
860:LPRINT USING "
    #########";H
865:NEXT C
866:U=U/60,G=500
867:GOSUB 950
869:S1=S
870:ROTATE 0
875:GLCURSOR (0,0)
877:LINE -(0,-500)
880:GLCURSOR (0,0)
885:FOR C=0TO 500
    STEP 10
987:GLCURSOR (0,-C
    )
890:GLCURSOR (-24,
    -C)
892:CSIZE 1
895:H=C*S
897:LPRINT USING "
    ####";H
900:NEXT C
910:K=NJ,NJ=2,UJ=U
    3
912:GOSUB 600
915:Y1=T3/60
917:NJ=K
920:GOSUB 600
922:Y2=T3/60
925:COLOR 3
926:GLCURSOR (0,0)
930:GLCURSOR (2/S2
    ,-Y1/S1)
935:LINE -(NJ/S2,-
    Y2/S1)
940:GOTO 1020
950:S=.1
955:IF U>S*GGOTO 9
    60
957:GOTO 965
960:S=S*10
962:GOTO 955
965:IF S=.1GOTO 98
    0
970:S=S/10
972:S=S+.1
975:IF U<=S*GGOTO
    980
977:COTO 972
980:RETURN
1000:PRINT "END O
     F PROGRAM"
1001:END
1020:K=NJ,NJ=2,UJ
     =U2
1022:GOSUB 630
1025:Y1=T2/60
1027:NJ=K
1030:GOSUB 630
1032:Y2=T2/60
1035:COLOR 2
1037:GLCURSOR (0,
     0)
1040:GLCURSOR (2/
     S2,-Y1/S1)
1042:LINE -(NJ/S2
     ,-Y2/S1)
1043:GOSUB 1180
1045:CSIZE 2
1050:COLOR 0
1055:GLCURSOR (17
     8,-510)
1060:ROTATE 1
1065:LPRINT USING
     "####.##"; T
     OTAL TIME MO
     DEL I=";T3/6
     0
1070:GLCURSOR (15
     8,-510)
1075:LPRINT "TOTA
     L TIME MODEL
      II=";T2/60
1080:GLCURSOR (13
     8,-510)
1085:LPRINT "MODE
     L I % UNACC.
      S/J=";U3*10
     0
1090:GLCURSOR (11
     8,-510)
1095:LPRINT "MODE
     L II % UNACC
     . S/J=";U2*1
     00
1100:GLCURSOR (98
     ,-510)
1105:LPRINT "TIME
      STUDY DATA=
     "
1110:GLCURSOR (78
     .-510)
1115:LPRINT "TH="
     :TH;"TS=";TS
     ;"TC=";TC;"T
     M=";T1
1120:GLCURSOR (58
     .-510)
1125:LPRINT "TR="
     :TR;"TJ=";TJ
     ;"PI=";P1;"P
     C=";PC
1130:GLCURSOR (38
     .-510)
1135:LPRINT USING
      #####"; NUM
     BER S/J THIS
      PCA=";NJ
1140:GLCURSOR (18
     .-510)
1145:LPRINT USING
     "###.#"; "%Q.
     C BURDEN,MOD
     EL I/II=",X,
     "/";Y
1150:COTO 1000
1180:CSIZE 1
1185:GLCURSOR (18
     8,-325)
1190:ROTATE 1:
     COLOR 0
1195:LPRINT "MODE
     L I=RED.MODE
     L II=GREEN"
1200:RETURN
```

Model I, Scheme 3 vs. Model II computer program runs:

* Graph Set A:

Depicts a computer program run of each model set using a 150 solder joint (S/J) PCA as the item of interest. Time study parametrics for the baseline graph are essentially the same as those that were used in development of the simplified algorithms.

Graph (1) Baseline Model Set
Graph (2) T_m (Time-to-Mark Event) reduced by 15 seconds
Graph (3) Excessive touch-up by ≈ 5%
Graph (4) Excessive touch-up by 20%

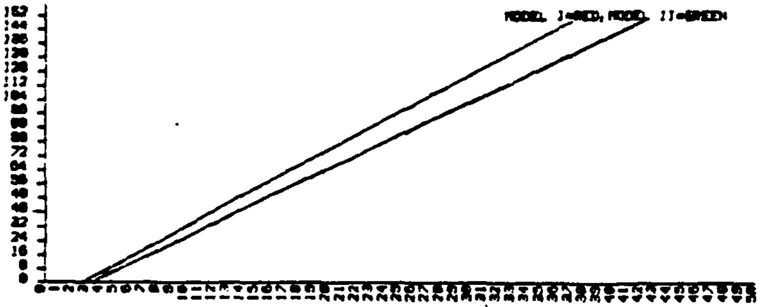
* Graph Set B:

Depicts a computer program run of each model set using a 1300 solder joint (S/J) PCA as the item of interest.

Graph (1) Baseline Model Set
Graph (2) Excessive touch-up by 4.5% (6% vs. 1.5%)
Graph (3) Excessive touch-up by 4.5% & T_s (Time-to-Scan Event) reduced one-fourth
Graph (4) Excessive touch-up by 4.5% & T_m (Time-to-Mark Event) reduced one-fourth

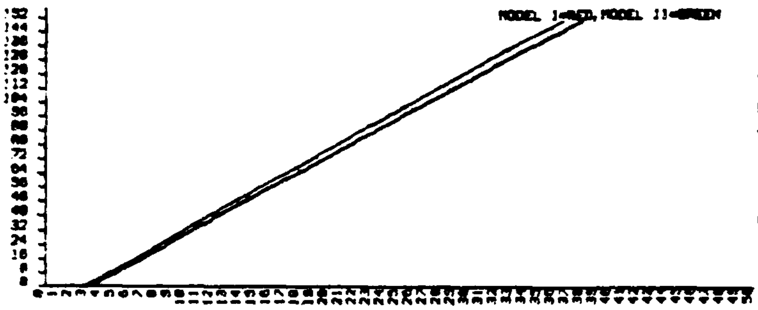
* Ordinate = Number S/J; Absissca = time, in minutes.

Graph Set A



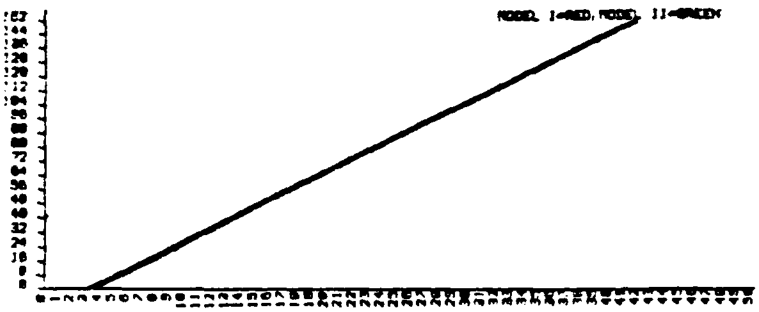
TOTAL TIME MODEL I= 42.23
TOTAL TIME MODEL II= 37.22
MODEL I % UNACC. S/J= 10.00
MODEL II % UNACC. S/J= 10.00
TIME STUDY DATA=
TH= 15.00TS= 5.00TC= 30.00TM= 25.
TR= 30.00TJ= 8.33PI= 0.04PC= 0.
NUMBER S/J THIS PCA= 150
%Q.C BURDEN, MODEL I/II= 76.3/ 35.5

(1)



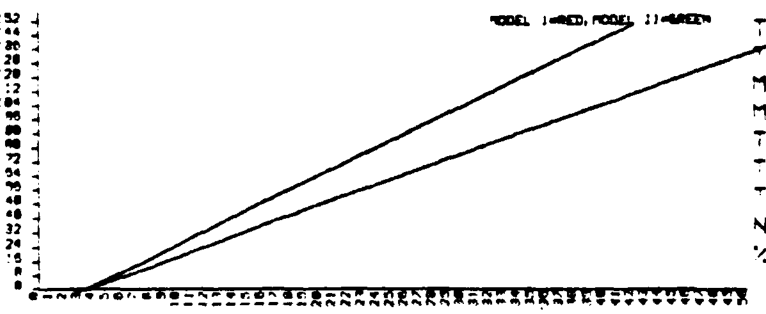
TOTAL TIME MODEL I= 38.35
TOTAL TIME MODEL II= 37.08
MODEL I % UNACC. S/J= 10.00
MODEL II % UNACC. S/J= 10.00
TIME STUDY DATA=
TH= 15.00TS= 5.00TC= 30.00TM= 10.00
TR= 30.00TJ= 8.33PI= 0.04PC= 0.04
NUMBER S/J THIS PCA= 150
%Q.C BURDEN, MODEL I/II= 74.2/ 35.3

(2)



TOTAL TIME MODEL I= 42.23
TOTAL TIME MODEL II= 42.23
MODEL I % UNACC. S/J= 10.00
MODEL II % UNACC. S/J= 15.14
TIME STUDY DATA=
TH= 15.00TS= 5.00TC= 30.00TM= 25.00
TR= 30.00TJ= 8.33PI= 0.04PC= 0.04
NUMBER S/J THIS PCA= 150
%Q.C BURDEN, MODEL I/II= 76.3/ 31.6

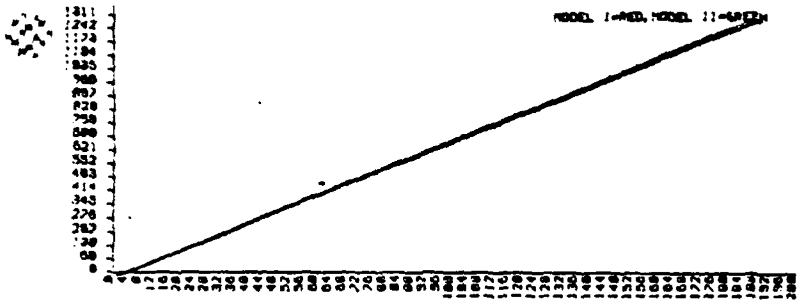
(3)



TOTAL TIME MODEL I= 42.23
TOTAL TIME MODEL II= 56.68
MODEL I % UNACC. S/J= 10.00
MODEL II % UNACC. S/J= 30.00
TIME STUDY DATA=
TH= 15.00TS= 5.00TC= 30.00TM= 25.00
TR=.30.00TJ= 8.33PI= 0.04PC= 0.04
NUMBER S/J THIS PCA= 150
%Q.C BURDEN, MODEL I/II= 76.3/ 24.2

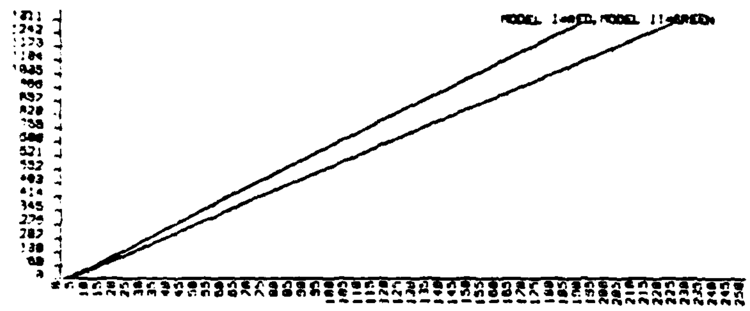
(4)

Graph Set B



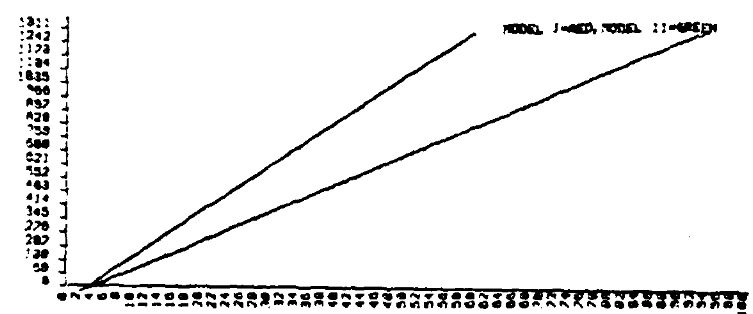
TOTAL TIME MODEL I= 190.56
TOTAL TIME MODEL II= 187.55
MODEL I % UNACC. S/J= 1.50
MODEL II % UNACC. S/J= 1.50
TIME STUDY DATA=
TH= 10.00TS= 4.00TC= 20.00TM= 12.00
TR= 34.00TJ= 4.50PI= 0.02PC= 0.02
NUMBER S/J THIS PCA= 1300
%Q.C BURDEN, MODEL I/II= 93.3/ 46.4

(1)



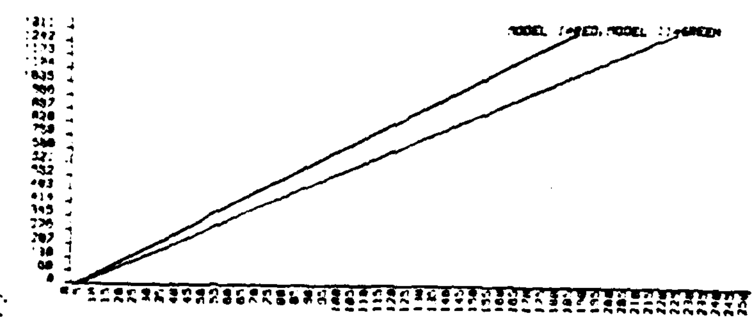
TOTAL TIME MODEL I= 190.56
TOTAL TIME MODEL II= 225.22
MODEL I % UNACC. S/J= 1.50
MODEL II % UNACC. S/J= 6.00
TIME STUDY DATA=
TH= 10.00TS= 4.00TC= 20.00TM= 12.00
TR= 34.00TJ= 4.50PI= 0.02PC= 0.02
NUMBER S/J THIS PCA= 1300
%Q.C BURDEN, MODEL I/II= 93.3/ 38.7

(2)



TOTAL TIME MODEL I= 60.56
TOTAL TIME MODEL II= 95.22
MODEL I % UNACC. S/J= 1.50
MODEL II % UNACC. S/J= 6.00
TIME STUDY DATA=
TH= 10.00TS= 1.00TC= 20.00TM= 12.00
TR= 34.00TJ= 4.50PI= 0.02PC= 0.02
NUMBER S/J THIS PCA= 1300
%Q.C BURDEN, MODEL I/II= 79.0/ 23.4

(3)



TOTAL TIME MODEL I= 187.58
TOTAL TIME MODEL II= 224.99
MODEL I % UNACC. S/J= 1.49
MODEL II % UNACC. S/J= 6.00
TIME STUDY DATA=
TH= 10.00TS= 4.00TC= 20.00TM= 3.00
TR= 34.00TJ= 4.50PI= 0.02PC= 0.02
NUMBER S/J THIS PCA= 1300
%Q.C BURDEN, MODEL I/II= 93.2/ 38.7

(4)

TRANSITIONING ENGINEERING DESIGNS TO PRODUCTION

EZRA SHEFFRES

RAYTHEON COMPANY
LEXINGTON, MA

ROLE OF THE COMPANY

- PRODUCE AN ACCEPTABLE END PRODUCT
- MEET ALL CONTRACTUAL REQUIREMENTS
  - PERFORMANCE
  - RELIABILITY
  - FORM FACTORS

HOW DO WE ACCOMPLISH THIS

DESIGN

↓

TEST and INTEGRATION

↓

RELEASE to MANUFACTURING ← TRANSITION POINT

↓

PROCUREMENT

↓

MANUFACTURING and QUALITY

↓

FIELD

MAJOR OBSTACLE TO A SUCCESSFUL PROGRAM IS THE TRANSITION OF THE ENGINEERING DESIGN TO PRODUCTION.

- UNRESOLVED ENGINEERING PROBLEMS
- PRODUCIBILITY PROBLEMS
- NON-STANDARD PART PROBLEMS
- TESTABILITY PROBLEMS

- TRANSITION PHASE MUST START WITH DESIGN
- RELEASE TO MANUFACTURE IS TOO LATE TO CORRECT DEFICIENCIES
- COMMON PROBLEM OF FRONT END FUNDING

HOW DO WE ACCOMPLISH THIS

- GOOD ENGINEERING DESIGN - BASE LINE
- MATHEMATICAL SYSTEMS EVALUATION
- RELIABILITY PREDICTIONS & TESTING
- TOTAL TEST PROGRAM
- GOOD MANUFACTURING PRACTICES
- QUALITY CONTROL EVALUATIONS
- FIELD HISTORY EVALUATION
- CORRECTIVE ACTION & SOLUTIONS

TOTAL COMPANY RESOURCES MUST BE USED

ENGINEERING

RELIABILITY

MANUFACTURING

QUALITY CONTROL

HUMAN FACTORS - INTERFACES BECOME PARAMOUNT

ENGINEERING AND MANUFACTURING MUST WORK TOGETHER

RELIABILITY FIELD DATA

FIELD DATA

PROGRAM	CONTRACTURAL MTBF	MTBF
SHIPBOARD EW SYSTEMS	332	611
	196	695
	166	250
AIRBORNE EW SYSTEMS	200	200
	165	300
SHIPBOARD SEARCH RADAR	300	550
	142	170
SHIPBOARD FIRE CONTROL SYSTEM	100	101
PHASED ARRAY RADAR	100	330
AIR-TO-AIR MISSILE	240 CAPTIVE CARRY	882 CAPTIVE CARRY
AIR-TO-AIR MISSILE	450	577 CAPTIVE CARRY
	1,500	1,072
SONAR SYSTEMS	600	974
	200	916

LONG RUN PRODUCTION PROGRAMS SHOW GOOD RESULTS

TRANSITION PROBLEMS

THREE CLASSES OF PROGRAMS

GOOD PROGRAMS FROM INCEPTION THROUGH PRODUCTION

PHASED ARRAY RADARS	

PROGRAMS WITH DEVELOPMENTAL DIFFICULTIES SOLVED PRIOR TO PRODUCTION

SHIPBOARD SEARCH RADAR	EXTENSIVE TEST-ANALYSIS-FIX PROGRAM
SHIPBOARD EW SYSTEMS	SAME AS ABOVE
AIR-TO-AIR MISSILE	EXTENSIVE RELAIBILITY IMPROVEMENT PROGRAM

PROGRAMS WITH DEVELOPMENTAL DIFFICULTIES NOT SOLVED PRIOR TO PRODUCTION

AIR-TO-AIR MISSILE	CONTINUED SHIPMENT AND EVALUATION WITH KNOWN PROBLEMS
AIRBORNE EW SYSTEM	PROBLEMS NOT SOLVED AT PROTOTYPE STAGE
SONOBOUY	PROBLEMS DISCOVERED IN PRODUCTION ACCEPTANCE TESTS
FIRE CONTROL SYSTEM	WORKMANSHIP PROBLEMS IN LARGE SYSTEM

PRESENT DAY PROGRAMS MUST BE DESIGNED AND TESTED TO KNOWN RESTRICTIVE ENVIRONMENTS AND ALL PROBLEMS CORRECTED PRIOR TO INITIAL PRODUCTION

WE KNOW WHAT TO DO - WE KNOW HOW TO DO IT - WE NEED TO DISCIPLINE OURSELVES

WHAT MAKES GOOD QUALITY

FOUR AREAS OF PRIMARY CONCERN:

- DESIGN
- COMPONENT SELECTION
- IN-PROCESS TEST & SCREENING
- WORKMANSHIP

DESIGN

ADEQUACY OF DESIGN

- COMPUTER-AIDED-DESIGN
- DESIGN GUIDELINES
- TESTABILITY EVALUATION
- TEST ANALYSIS & FIX PROGRAMS (TAAF)
- QUALIFICATION TESTING
- RELIABILITY & MAINTAINABILITY DEMONSTRATIONS

30

COMPONENT SELECTION

STANDARD PARTS SYSTEM

- USE OF MIL APPROVED PARTS
- STOCKING OF ENGINEERING STORES WITH STANDARD PARTS

DEVELOPMENT OF APPROVED VENDOR LIST

RIGOROUS NON-STANDARD PARTS PROGRAM

IN-PROCESS TEST & SCREENING

COMPONENT PRE-CONDITIONING & SCREENING

- FULL MIL-STD-883 TESTING

LIMITED ENVIRONMENTAL TESTING

- VIBRATION
- TEMPERATURE CYCLING
- THERMAL SHOCK
- BURN-IN

TESTING VARIES WITH PRODUCT REQUIREMENTS

NEED TO EVALUATE MINIMUM SCREENING TESTS

WORKMANSHIP

UTILIZE STANDARDS OF WORKMANSHIP

OPERATOR TRAINING & CERTIFICATION OF OPERATION

- WELDING
- SOLDERING
- NON-DESTRUCTIVE TESTING
- BONDING

MOTIVATION

- TOUCH LABOR
  - ZERO DEFECTS PROGRAM
  - WORKMANSHIP EXCELLENCE PROGRAM
  - QUALITY CIRCLES
  - SUGGESTION PROGRAMS
- EXEMPT AND MIDDLE MANAGEMENT
  - EDUCATION SEMINARS
  - TECHNOLOGY GROUPS
  - PROVIDE QUALITY FORUM

RECOMMENDATIONS

DEVELOP STANDARD MEASURES OF QUALITY FOR INDIVIDUAL PLANTS & PROGRAMS

- PRODUCT ACCEPTANCE YIELDS AT KEY POINTS IN THE MANUFACTURING PROCESS
- MEASURE FIELD VS CONTRACTUAL RELIABILITY

MONITOR RELIABILITY STATUS OF DEVELOPING PROGRAMS

- ENGINEERING PHASE
- INITIAL FACTORY BUILD
- INITIAL CUSTOMER TEST AND EVALUATION

PERFORM SYSTEM AUDITS OF FIELDED HARDWARE

COMMUNICATE UPPER MANAGEMENT QUALITY MESSAGE

DEVELOP IMPROVED MOTIVATIONAL PROGRAMS

- FOR TOTAL COMPANY
- FOR ALL LEVELS OF PERSONNEL

THE HIDDEN FACTORY

by Jim Kuhlemeier and Garland Linde

Honeywell's Defense Systems Division has supplied lightweight torpedoes to the U.S. Navy since 1965. A few years ago, the company invested several million dollars in facilities and a factory modernization program for this antisubmarine weapon. Although our major investment gave us the finest torpedo facility in the country, in September 1980 we were failing to meet our schedules. Despite the advanced facilities and a skilled work force, too many defects were coming off the lines—some of the torpedo's more complex equipment, the receiver for example, was reworked for minor defects 16 times before acceptance.

Honeywell invested several million dollars in its torpedo manufacturing facility and a factory modernization program.

High final torpedo acceptance rates had created a smokescreen, leading us to believe that our manufacturing process was actually more successful than it was. Traditional tracking methods failed to precisely identify the excessive rework with its accompanying high costs and manpower utilization.

With the help of the Navy, Honeywell planned an attack on the problem and set into motion an intensive 2-year program that involved several hundred people, from vice presidents to line operators.

Navy review

After learning about Honeywell's schedule difficulties, the Naval Material (NAVMAT) Office offered to review our factory processes. During their visit, they focused on the rework cycle and observed that torpedo assemblies were circling through a round robin of rework operations; multiple processing of material resulted in severe reduction not only in the factory's productive capacity but in the inherent reliability of the material as well. After a thorough review of the facility, the NAVMAT staff suggested a concentrated attack on the causes behind the excessive rework cycle, which they called, the "Hidden Factory." Both NAVMAT and Honeywell felt that a successful defect reduction program would substantially reduce work and achieve schedules without additional factory personnel

"Do it right the first time!"

Our first task was to analyze the torpedo manufacturing process, searching rejection data for the major rework areas. This information furnished a baseline for review by teams of Production and Quality engineers. After identification, the high cost, major rework areas were selected for process remodeling, data reporting and operator aid improvements. In addition, arrangements were made for regular management monitoring of the program and a motto was chosen: "Do it right the first time!"

Listening to the people

Setting program goals was not too difficult, but achieving them was a challenge. Our program had been communicated to Manufacturing, Engineering and Management, and now it was time to listen to the people on the production lines. Quality Circles of Production and Inspection operators were formed, and we asked for their ideas. The response was enthusiastic. The Circles analyzed their areas and held "brainstorming" sessions aimed at reducing rework to zero defects. Added to this factory self-analysis was input from an industry review team. Visits, coordinated by NAVMAT, were made to six companies, and we returned with ideas for manufacturing process improvements and capital equipment applications in several areas, including wave soldering and connector assembly aids.

Milestone plan

The next step was to take all ideas—from NAVMAT, the engineers, Quality Circles, and our industry review team—to construct a milestone plan for tracking the program. The agreed-upon goals for the major manufacturing areas were integrated with time-phased corrective action events pointing to zero defects (Figure 1). These goals were not changed during the first year of factory improvement because Honeywell's management wanted to maintain a firm base for measurement of all improvements and consistency of reporting. This did not mean, however, that the program was not flexible enough to absorb changes as new and better ideas were offered.

Management support

We were off and running with a program guaranteed priority, a priority that could override schedules when there was conflict. Don Pelletier, Manager of Factory Operations, explains: "When we began the defect reduction program, management realized that considerable pain would be incurred in overcoming the rework problem. Despite schedule pressures and risks associated with delinquencies, we decided that compromise was out of the question if we were to succeed. At no time during the two years did we sacrifice quality to achieve a schedule. There was indeed pain, but we bettered our schedule performance . . . and our cost picture. We reduced rework, cut lead times in the factory, and now are more confident that material in the assembly process will be delivered to our requirements." Our rationale, then, was that elimination of the Hidden Factory would resolve schedule slips in the long run.

Management also strengthened the program by approving a cost plan for manpower, capital tooling and facility requirements. "We were absolutely committed to dedicating the necessary resources for resolving our production problems," stated Gene Haisting, Director of Product Assurance. "It had taken some time to get into this position, and we knew it would take time to get us out. However, our persistence paid off. We have just completed 225 torpedoes without a hardware final test rejection."

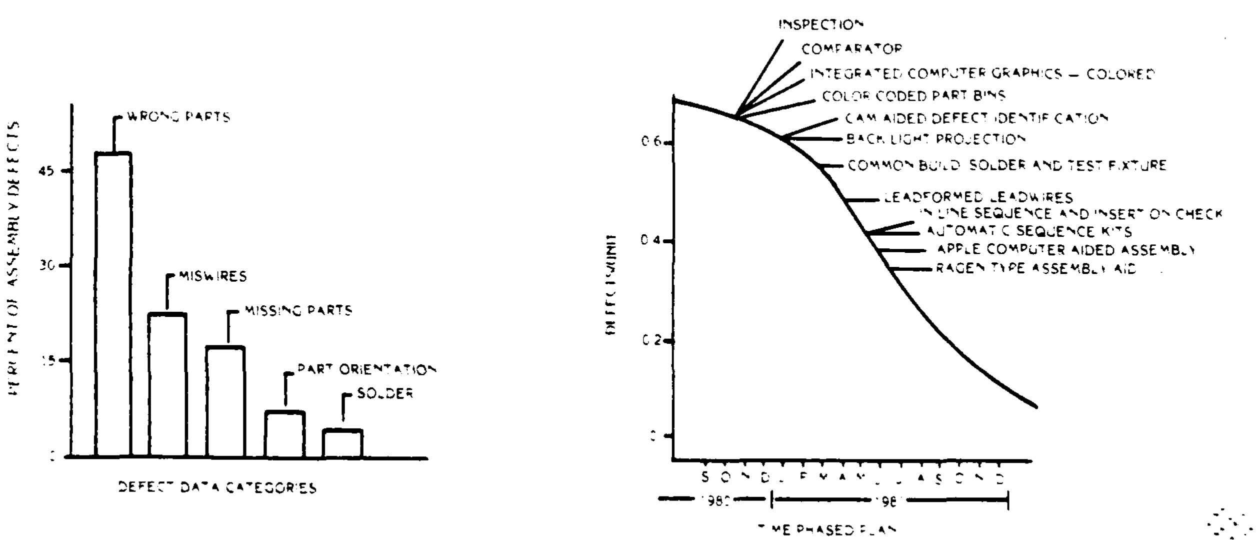


Figure 1. Our time-phased defect reduction plan was key to zero defect monitoring.

Operator-dependent production

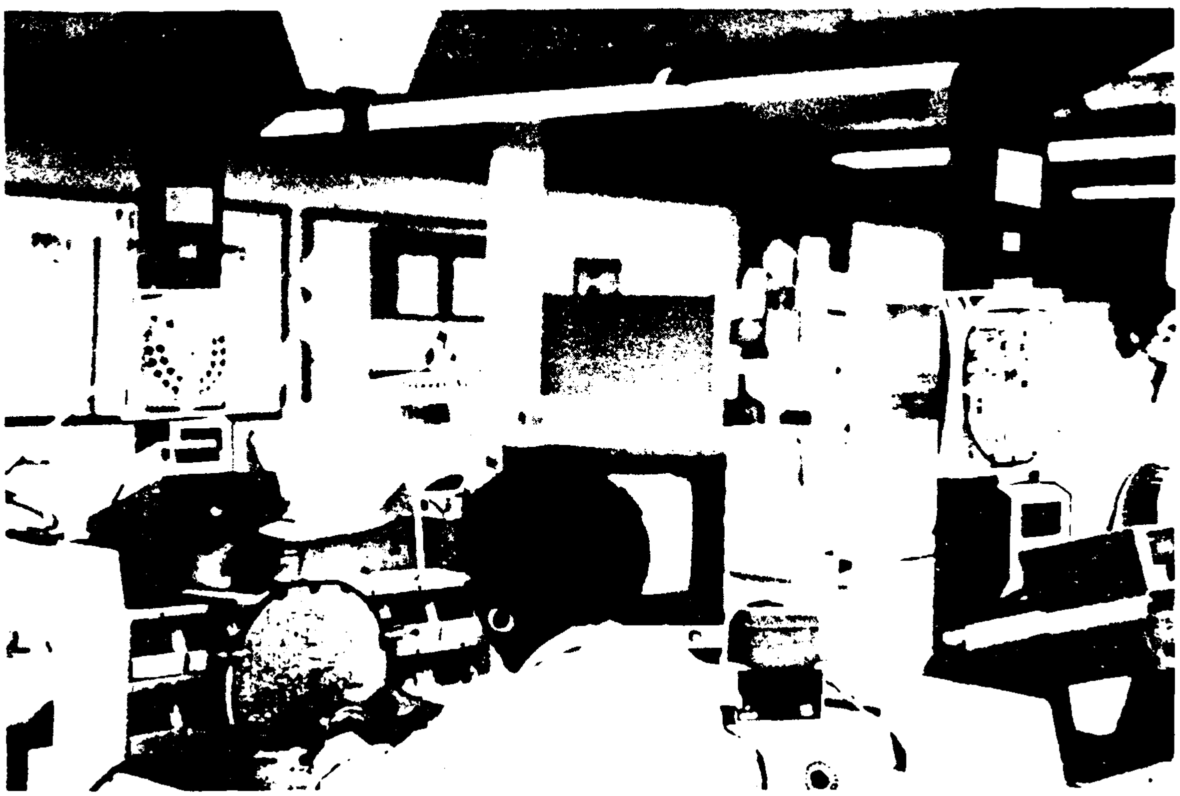
In the early phases of the program, it was apparent that production was highly dependent upon operator capability and that improvement must be channeled toward operator aids. Mk 46 build processes were difficult for new operators and not conducive to rapid operator learning.

Honeywell had been experiencing significant worker turnover due to cutbacks in the Residential Division work force. Residential union members were taking over positions of trained Mk 46 employees with less seniority, which mandated development of processes to reduce training time. The Quality teams concentrated on places where we could make jobs less dependent on operator technique and more dependent on tools and equipment.

As soon as the engineers finished identification of areas for potential improvement in the factory, management quickly approved capital expenditure plans for needed production operator-aid tooling. We employed Apple computers extensively to replace paperwork instructions in the harness assembly area, and purchased semi-automatic component assembly machines (DYNA/CAMS and Ragens) to replace hand assembly operations. We also installed a transporter material handling system for use with the Ragens and DYNA/CAMS. Finally, we implemented tooling overlays, colored graphics, computerized graphics, improved fixturing and new work station layouts, and expanded the work area. The improvements were scheduled, their contribution to the rework reduction estimated, and all action and results monitored and tracked by the respective task teams.

No more complacency

Working with each other, the teams often found entirely new ways of performing their jobs and improving factory processes. In the Ragen/Cable Scan operation, an engineering brainstorming session produced the idea of "marrying" two diverse pieces of equipment with an electronic interface. Implementation of this concept provides the operator with an audible "beep" when the proper lead wire was selected. Simultaneously, a light beam indicates the proper termination point. This unique system reduced operator errors and showed the importance of engineering innovation. We have continued to challenge our engineers so that they do not become complacent and assume that machines alone will do the job.



An engineering brainstorming session produced the idea of "marrying" two diverse pieces of equipment—the Ragen/Cable Scan.

A factory under control

During the 2-year improvement period, the time required to build a Mk 46 torpedo was driven down by 66 percent (Figure 2), while the build rate per month was doubled. Also, the visual defect rate was reduced by over 70 percent. Now that a dramatic improvement in productivity was achieved, we could focus on still other areas to promote efficiency. One was establishment of a new Learning Center designed for training engineers and operators. The center's philosophy is that people want to perform well. The task is to teach the criteria of good workmanship, certify operators to those standards, and institute procedures to ensure adherence.

Our Learning Center is also an experimental area for "hands-on" evaluation of new equipment and tooling. Engineers are able to develop new processes and get bugs out before putting the equipment on line. Factory operators participate in this debug process and are extremely enthusiastic about having a chance to "get their oar in" before the system hits the line.

A model factory

All the ingredients for a successful program existed at Honeywell: management commitment of interest, time and money; and an enthusiastic response by people involved in the factory's day-to-day operation to a difficult challenge. Those associated with this program knew the satisfaction of improving their own factory and seeing application of their ideas to other Honeywell production areas, including the Avionics Division's gyro assembly lines. Our torpedo factory has become a showplace for process improvement, with visitors from many o[illegible] companies coming to examine our processes.

Clint Larson, Vice President of Honeywell's Underseas Systems Operations, believes that "this kind of free exchange benefits all of us. For many years, defense contractors guarded their manufacturing processes and technologies from other companies. Only recently has there been a sharing of ideas and techniques, which has meant industry-wide manufacturing and profit improvements. We have learned from others and will continue to share our ideas and processes with them."

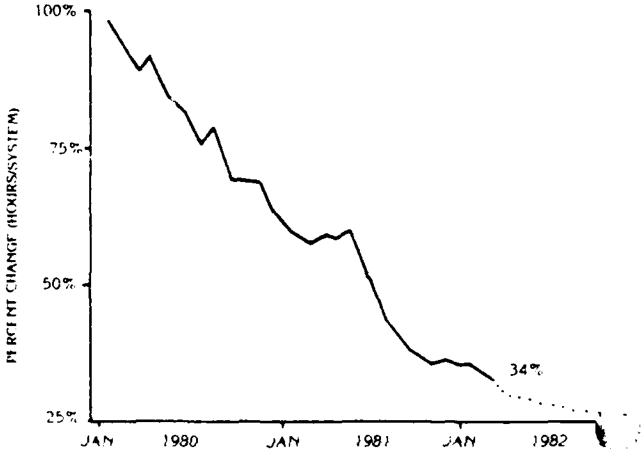


Figure 2. Emphasis on producibility, reliability and quality reduced factory hours by 66 percent.

Jim Kuhlemeier received a BSEE from the University of Wisconsin in 1968 and an MBA from the University of Minnesota in 1974. Mr. Kuhlemeier has been a member of the Quality Assurance Department since joining Honeywell in 1968. He has spent over 13 years on the Torpedo Mk 46 program, working as an engineer, supervisor and currently as the Quality Assurance Manager.

Garland Linde is currently the Production Engineering Section Chief for the Mk 46 torpedo at Honeywell [illegible]derseas Systems Division. He received his BSE[illegible] 1959, and has since been engaged in assembly and test on guidance, flight control and fire control systems for torpedoes, aircraft and spacecraft.

ORGANIZATIONAL STRUCTURE
THE EFFECTIVENESS OF THE QUALITY FUNCTION

C. E. SEEGER
Director, Quality Assurance
General Dynamics Pomona Division

WHEN I FIRST PROPOSED TO OFFER A FEW COMMENTS ON THIS TOPIC, IT SEEMED LIKE A GOOD IDEA. I HAD BEEN HEADING A LARGE QUALITY ASSURANCE DEPARTMENT FOR SEVERAL YEARS IN A COMPANY WITH A DYNAMIC AND GROWING BASE OF PRODUCTION PROGRAMS AND ENGINEERING PROGRAMS. THERE WERE ABOUT 760 PERSONNEL IN MY DEPARTMENT; I HAD A GROUP OF OUTSTANDING MANAGERS TO RUN THE ORGANIZATION SMOOTHLY AND EFFICIENTLY, AND AS DIRECTOR, I REPORTED DIRECTLY TO THE DIVISION GENERAL MANAGER AND WAS A MEMBER OF HIS STAFF. THE GENERAL MANAGER WAS A STRONG PROPONENT OF QUALITY, HIS POLICY WAS CLEAR, AND THE PROGRAM AND FUNCTIONAL ORGANIZATIONS AND PERSONNEL WERE ALWAYS WELL AWARE OF HIS POSITION REGARDING THEIR RESPONSIBILITY FOR PRODUCT QUALITY. I MENTION THIS LAST POINT SPECIFICALLY, BECAUSE SUCH AN ENVIRONMENT ENHANCED SIGNIFICANTLY MY ABILITY TO RESOLVE ISSUES OR PROBLEMS RELATED TO QUALITY AT A PROGRAM DIRECTOR OR LINE DIRECTOR LEVEL WITHOUT HAVING TO "GO TO COURT" OR ELEVATE MATTERS TO THE GENERAL MANAGER. WHEN YOU HAVE DIRECT ACCESS TO THE GENERAL MANAGER AND HAVE HIS SUPPORT BEHIND YOU, IT'S RELATIVELY EASY TO CONVINCE A RECALCITRANT MANUFACTURING DIRECTOR OR PRODUCT LINE DIRECTOR THAT THE QA WAY IS THE RIGHT WAY - AND, OF COURSE, WE'RE ALWAYS RIGHT.

IN ANY EVENT, THE ORGANIZATIONAL ARRANGEMENT WAS FUNCTIONING EXTREMELY WELL. THE QUALITY ASSURANCE DEPARTMENT WAS THE INDEPENDENT FUNCTION THAT WE ALL AGREE IS NECESSARY, WE WERE ON A REPORTING LEVEL EQUAL TO DEPUTY GENERAL MANAGERS AND VICE PRESIDENTS THROUGHOUT THE DIVISION, AND THERE WAS NO HINT

OR THOUGHT OF ANY APPLIED INFLUENCE IN FAVOR OF COST OR SCHEDULE OVER QUALITY. THE ONLY DRAWBACK THAT I PERCEIVED WAS A LESS THAN ADEQUATE AMOUNT OF TIME AVAILABLE WITH THE GENERAL MANAGER ON A ROUTINE BASIS. ON ANY MATTERS OF AN URGENT NATURE I HAD IMMEDIATE ACCESS, BUT THE MYRIAD ACTIVITIES AND RESPONSIBILITIES INVOLVED IN OPERATING A LARGE FACILITY (8,000 EMPLOYEES), WITH MULTIPLE PROGRAMS AND CUSTOMERS, AND A VERY ACTIVE CORPORATE OFFICE, CERTAINLY KEPT THE GENERAL MANAGER EXTREMELY BUSY IN-PLANT, AND ON TRAVEL FREQUENTLY.

THIS WAS THE SITUATION "BEFORE", IN MY "BEFORE AND AFTER" EXPERIENCE. THE VU-GRAPH DEPICTS A SIMPLIFIED VERSION OF THE ORGANIZATION I HAVE JUST DESCRIBED. I SHOULD POINT OUT THAT IN THE 30 YEAR HISTORY OF THE COMPANY THERE HAVE BEEN MANY CHANGES AND RESTRUCTURING OF THE ORGANIZATION CHART, BUT THERE WAS ALWAYS A QA BLOCK ON THE CHART REPORTING TO THE GENERAL MANAGER.

ON 21 DECEMBER, 1981 THE GENERAL MANAGER CALLED A SPECIAL STAFF MEETING, ON SHORT NOTICE. AS IN MANY COMPANIES, ANNOUNCEMENT OF THIS TYPE OF MEETING IS ALWAYS AN INDICATION THAT SOMEONE IS ABOUT TO BE PROMOTED OR TRANSFERRED, OR SOME MAJOR ORGANIZATIONAL CHANGE IS BEING EFFECTED. ON THIS OCCASION WE WERE NOT DISAPPOINTED. OR, I SHOULD SAY WE WERE DISAPPOINTED - IT DEPENDED ON WHICH BLOCK IN THE ORGANIZATION CHART YOU FILLED. ANYWAY, (EFFECTIVE IMMEDIATELY, OF COURSE) MOST OF THE PROGRAM FUNCTIONS WERE REALIGNED TO REPORT DIRECTLY TO THE GENERAL MANAGER, AND MOST OF THE LINE FUNCTIONS WERE RELOCATED TO POSITIONS REPORTING TO ONE OF THE TWO DEPUTY GENERAL MANAGERS. QUITE PROMINENT IN THE NEW STRUCTURE, AS SEEN IN THIS SLIDE, IS THE POSITION OF THE QUALITY ASSURANCE DEPARTMENT, NOW REPORTING TO THE DEPUTY GENERAL MANAGER - OPERATIONS.

NEEDLESS TO SAY, I WAS SLIGHTLY UNSETTLED BY THE CHANGE. MY INITIAL REACTION WAS A PERCEPTION THAT THE ENTIRE QA DEPARTMENT HAD BEEN DEMOTED, THAT I WOULD LOSE MY INDEPENDENT ROLE, THAT I WOULD BE SUBJECTED TO ALL THE HORRORS OF COERCION AND INFLUENCE BY THE OPERATIONS GROUP WHO WOULD TREAT QUALITY AS A DISTANT

THIRD PRIORITY BEHIND SCHEDULE AND COST, THAT A NEW AND EASY WAY TO REDUCE OPERATIONS' COSTS WOULD BE TO CUT THE INSPECTION FORCE IN HALF, AND THAT ANY EFFORTS ON MY PART TO UPHOLD QUALITY INTEGRITY AT THE EXPENSE OF SCHEDULE WOULD BE LOOKED UPON UNFAVORABLY BY THE SAME PERSON WHO WOULD BE WRITING MY PERFORMANCE APPRAISAL AND GIVING MY ANNUAL MERIT REVIEW.

THAT I'M STANDING HERE TODAY TALKING ABOUT THIS IS TESTIMONY TO THE FACT THAT THESE REACTIONS OR CONCERNS DID NOT HAPPEN AND THE ORGANIZATIONAL CHANGE DID NOT DESTROY THE EFFECTIVENESS OF OUR QA ORGANIZATION. IN FACT, I BELIEVE WE MADE MORE PROGRESS DURING THE LAST YEAR THAN DURING PREVIOUS YEARS. AND, I HAVE TO BE CAREFUL WHEN I SAY THAT, BECAUSE I DON'T WANT TO APPEAR NEGATIVE OR CRITICAL TOWARD THE GENERAL MANAGER. THAT, IN ITSELF, COULD BE CAREER LIMITING. IN A FEW MINUTES I'LL OUTLINE A FEW OF THE INITIATIVES AND BENEFITS WE DERIVED IN THIS NEW ENVIRONMENT.

THERE WAS AN INITIAL TRANSITION PERIOD THAT HAD TO BE TRAVERSED. DIFFERENT MANAGEMENT STYLES REQUIRED SOME ADJUSTMENTS, MY DEPARTMENT MANAGERS AND OTHER PERSONNEL HAD TO BE REASSURED, OR CONVINCED, THAT THEY WOULD BE ABLE TO OPERATE AS BEFORE (BECAUSE, OF COURSE, I WAS NOT THE ONLY PERSON IN THE QA DEPARTMENT WHO HAD MISGIVINGS), AND WE NATURALLY HAD TO OVERCOME SOME IMMEDIATE OBJECTIONS AND UNHAPPINESS BY OUR PRIMARY MILITARY CUSTOMERS.

AFTER THE FIRST MONTH, I THINK IT BECAME OBVIOUS TO ALL CONCERNED THAT OUR CONCERNS WERE UNFOUNDED AND OUR PROBLEMS MINIMAL. THERE WERE NO ORGANIZATIONAL OR PERSONNEL CHANGES MADE WITHIN THE QA DEPARTMENT, AND AS FAR AS MY MANAGERS AND THEIR PERSONNEL WERE CONCERNED, NOTHING HAD HAPPENED AT ALL. I ASSUMED THE

BUFFER, OR FILTER, ROLE IN THE NEW SET-UP AND WE MAINTAINED OUR PREVIOUS POSTURE COMPLETELY.

WE ADJUSTED TO THE NEW OPERATIONS PROCEDURES, A FEW MORE REPORTS WERE REQUIRED, A FEW MORE MEETINGS TO ATTEND, AND AN EXTRA SIGNATURE OR TWO HERE OR THERE.

THE CUSTOMER CONCERNS SOON DISAPPEARED AS THEY OBSERVED NO DILUTION OR LESSENING OF THE QUALITY ASSURANCE EFFORT.

HOW WAS SUCH AN ABRUPT CHANGE EFFECTED AND HOW WAS SUCH A DRASTIC DEPARTURE FROM OUR PAST ENVIRONMENT ACHIEVED WITH SUCH POSITIVE RESULTS? IN MY OPINION, THE KEY RESTS WITH THE INDIVIDUALS INVOLVED - THE HEAD OF THE OPERATIONS FUNCTION AND THE HEAD OF THE QUALITY FUNCTION. IF THEY HAVE INTEGRITY, RESPECT EACH OTHER, AND CAN WORK IN HARMONY AS A TEAM TOWARD THE DIVISION GOALS, SUCH AN ORGANIZATIONAL STRUCTURE CAN WORK VERY WELL.

I WAS FORTUNATE IN THIS INSTANCE, IN THAT THE DEPUTY GENERAL MANAGER - OPERATIONS WAS A SUPERB MANAGER, AGGRESSIVE, DEMANDING, AND INNOVATIVE. HE RECOGNIZED THE SIGNIFICANCE OF HAVING QUALITY ASSURANCE IN HIS GROUP, AND HE ASSUMED COMPLETELY HIS RESPONSIBILITY FOR THE QUALITY FUNCTION. AS A MEMBER OF HIS STAFF, I WAS ABLE TO PARTICIPATE FREELY IN EVERY FACET OF THE OPERATIONS DEPARTMENT ROUTINE. ATTENDANCE AT OPERATIONS STAFF MEETINGS AND OTHER DECISION MAKING MEETINGS PROVIDED AN OPPORTUNITY TO INJECT A QA VOICE OR VIEWPOINT THAT HAD NOT EXISTED BEFORE. INSTEAD OF BEING ON THE PERIPHERY OF OPERATIONS DEPARTMENT PLANNING, AS WAS THE CASE PREVIOUSLY, IN AREAS OF MODERNIZATION, TRAINING, FACILITY CHANGES, CAPITAL FACILITIES ACQUISITION, MOTIVATIONAL PROGRAMS, AND PRODUCTIVITY IMPROVEMENT PROGRAMS, AND OTHERS, I WAS ABLE TO ACT AS AN INTEGRAL PART OF THE TEAM WITH BENEFICIAL RESULTS FOR THE QUALITY FUNCTION.

THE MERGER OF MY DEPARTMENT WITH ONE WHICH WAS FOUR TIMES LARGER ALSO PROVIDED ME WITH MORE FLEXIBILITY IN THE MANPOWER, DIRECT, AND INDIRECT BUDGET AREAS.

WITH THE LARGER POOL OF ALLOCATED OR BUDGETED RESOURCES, REQUIRED VARIATIONS OR EXCURSIONS WERE POSSIBLE, AT THE DISCRETION AND WITH THE APPROVAL OF THE HEAD OF OPERATIONS.

SEVERAL QUALITY INITIATIVES WERE INSTITUTED DURING THE PAST YEAR, DIRECTED BY THE DEPUTY GENERAL MANAGER - OPERATIONS, AND SUPPORTED BY HIS STAFF AND PERSONNEL.

- MONTHLY QUALITY EXCELLENCE AWARD PROGRAM

  EACH MONTH AN OPERATIONS DEPARTMENT EMPLOYEE IS RECOGNIZED FOR HIS OR HER PERFORMANCE IN CONTRIBUTING TO THE QUALITY OF OUR PRODUCTS. NOMINEES ARE SUBMITTED BY SUPERVISORS AND SUPERINTENDENTS TO A QUALITY ASSURANCE DEPARTMENT PANEL CONSISTING OF THE QUALITY CONTROL MANAGER AND HIS FOUR CHIEFS OF INSPECTION, AND CHAIRED BY THE DIRECTOR OF QUALITY ASSURANCE. WE EVALUATE THE NOMINEES WITH REGARD TO THEIR WORK QUALITY, THEIR ABILITY TO DO IT RIGHT THE FIRST TIME, THEIR THOROUGHNESS IN FOLLOWING WORK INSTRUCTIONS, THEIR ALERTNESS AND INQUISITIVENESS IN CHALLENGING SOMETHING THAT DOESN'T LOOK RIGHT TO THEM, AND THEIR GENERAL ATTITUDE IN HELPING OTHER MEMBERS OF THE COST CENTER PRODUCE QUALITY WORK.

  THE PANEL SELECTS A WINNER, AND EVERY MONTH WE AWARD A CROSS PEN AND PENCIL SET AND A $200 U.S. SAVINGS BOND. THE AWARD IS MADE IN A BRIEF CEREMONY AT THE WORK AREA WITH PHOTOGRAPHS AND A WRITE-UP IN OUR MONTHLY EMPLOYEE NEWS PUBLICATION. WINNERS' NAMES ARE INSCRIBED ON A PERMANENT PLAQUE WHICH IS MOUNTED IN THE OPERATIONS AREA AND A LETTER IS MAILED TO EACH WINNER WITH A COPY TO THE PERSONNEL RECORD. THE PROGRAM HAS BEEN WELL RECEIVED WITH EXCELLENT SUPPORT AND PARTICIPATION.

- QUARTERLY QUALITY AWARD FOR COST CENTERS

  WE ARE NOW DEVELOPING SOME CRITERIA AND PROCEDURES TO BE USED FOR A MORE SUBSTANTIAL RECOGNITION AND MOTIVATION AWARD,

3.

- QUARTERLY QUALITY AWARD FOR COST CENTERS (CONTINUED)

  TO BE APPLIED TO MANUFACTURING COST CENTERS. THIS IS A LITTLE MORE CHALLENGING DUE TO THE VARIATIONS IN COMPLEXITY OF THE JOB PERFORMED AND THE SIZE AND NUMBER OF PERSONNEL IN THE COST CENTERS. WE WILL COMBINE, OR WEIGHT VARIOUS MEASUREMENTS SUCH AS SCRAP, REWORK, DEFECTIVES PER THOUSAND MANHOURS, REJECTION DOCUMENTS WITH THE TECHNICAL CONTENT OF THE WORK TO DETERMINE ELIGIBILITY FOR THE AWARD.

- MONTHLY HARDWARE TEAR DOWN PROGRAM

  IN 1982 WE IMPLEMENTED A PROGRAM CALLED "WORKMANSHIP VERIFICATION AND EVALUATION OF HARDWARE" - MORE GENERALLY REFERRED TO AS "TEAR DOWN INSPECTION". THE PROGRAM IS APPLIED ON ALL PRODUCTION PROGRAMS - STANDARD MISSILE, PHALANX, STINGER, AND SPARROW (WHICH IS MANUFACTURED AT OUR CAMDEN ARKANSAS FACILITY). THE PURPOSE OF THE TEAR DOWN INSPECTION PROGRAM IS TO PROVIDE A CONTINUOUS AND INDEPENDENT EVALUATION OF WORKMANSHIP QUALITY, PROCESS CONTROL, AND INSPECTION EFFICIENCY ON COMPLETED HARDWARE. THE METHODOLOGY OF THE PROGRAM INCLUDES:

  - RANDOM SELECTION OF HARDWARE AT VARIOUS LEVELS OF ASSEMBLY EACH MONTH, BY QUALITY ASSURANCE.
  - TEARDOWN/DISASSEMBLY TO THE LOWEST LEVEL POSSIBLE WITH MINIMUM DISCONNECT AND DESOLDER.
  - TEARDOWN IS ON HARDWARE THAT HAS BEEN EXPOSED TO ENVIRONMENTS WHICH ARE THE NORMAL PRODUCTION PROCESS.
  - EVALUATION IS PERFORMED BY SUPERVISORY PERSONNEL FROM MANUFACTURING, MANUFACTURING ENGINEERING, AND QUALITY ASSURANCE.

- RESULTS ARE DOCUMENTED ON WORKMANSHIP INCIDENT REPORTS.
- INSTANT FEEDBACK IS MADE TO OPERATORS, ASSEMBLERS, INSPECTORS OF ALL DISCREPANCIES FOUND.
- CORRECTIVE ACTION IS IMPLEMENTED AS NECESSARY THROUGH OUR EXISTING SYSTEMS.

THE PROGRAM REPRESENTS A JOINT EFFORT BY THE PRODUCTION PROGRAM OFFICE AND THE MANUFACTURING ORGANIZATION TO COMMIT RESOURCES AND TIME TO THIS ADDITIONAL VERIFICATION AND MEASURE OF HARDWARE WORKMANSHIP QUALITY. THE INSPECTIONS ARE SCHEDULED ON A WEEKLY OR MONTHLY BASIS DEPENDING ON THE LEVEL OF ASSEMBLY OF THE HARDWARE, AND PROVISIONS ARE MADE TO EXTEND OR DECREASE THE INTERVAL, DEPENDING ON THE NUMBER AND TYPE OF DISCREPANCIES FOUND.

- <u>FLOOR DISCIPLINE IMPROVEMENT PROGRAM</u>

THE OPERATIONS DEPARTMENT INSTITUTED A PROGRAM TO INCREASE QUALITY AWARENESS AND IMPROVE FLOOR DISCIPLINE IN FOLLOWING PRESCRIBED PROCEDURES, PROCESSES, AND GENERAL COMPLIANCE WITH GOOD MANUFACTURING PRACTICES. THE DEPUTY GENERAL MANAGER - OPERATIONS ESTABLISHED GOALS FOR THE REDUCTION OF DEFICIENCIES DETECTED DURING QA AUDITS IN 1982 FROM LEVELS ESTABLISHED DURING SIMILAR AUDITS IN 1981. ALL OPERATIONS DIRECTORS, MANAGERS, AND SUPERVISORY PERSONNEL HAVE COMMITTED TO THESE OBJECTIVES AND HAVE ESTABLISHED AWARENESS, ATTENTION-TO-DETAIL, AND TRAINING PROGRAMS TO ASSIST IN ACHIEVING THESE GOALS.

THE QUALITY ASSURANCE DEPARTMENT, BY MEANS OF UNSCHEDULED INFORMAL AUDITS CONDUCTED BY SUPERVISORY INSPECTION PERSONNEL, SCHEDULED FORMAL AUDITS BY THE QA AUDIT GROUP, AND AUDITS CONDUCTED BY NAVAL PLANT REPRESENTATIVE QUALITY ASSURANCE PERSONNEL,

REPORTS ON DEFICIENCIES DETECTED AND THE NUMBER OF HOURS EXPENDED IN AUDITS. THESE "DEFICIENCIES PER AUDIT HOUR" ARE REPORTED MONTHLY TO THE DEPUTY GENERAL MANAGER - OPERATIONS AND TO ALL OPERATIONS DEPARTMENT DIRECTORS. WE LIST THE DEPARTMENT "WHERE FOUND", DEPARTMENT "LIABLE", THE NUMBER, AND TYPE OF DEFICIENCIES NOTED.

THE VISIBILITY OF THIS PROGRAM WITH GOALS ESTABLISHED BY THE DEPUTY GENERAL MANAGER - OPERATIONS AND REGULAR REVIEW OF RESULTS AT OPERATIONS' STAFF MEETINGS MADE A SIGNIFICANT IMPACT IN 1982, WITH SUBSTANTIAL IMPROVEMENT THROUGHOUT THE FACTORY IN OUR DOCUMENTATION ACCURACY, THE COMPLIANCE TO WORK INSTRUCTIONS, CONTROL OF GAGES, TOOLS AND TEST EQUIPMENT, MATERIAL HANDLING AND CONTROL, CONFORMITY OF PROCESSING OPERATIONS TO SPECIFIED REQUIREMENTS, AND CONFORMITY OF THE PRODUCT TO SPECIFIED REQUIREMENTS.

- <u>DIVISION QUALITY IMPROVEMENT PROGRAM</u>

PERHAPS THE MOST SIGNIFICANT DEVELOPMENT DURING 1982, WHILE THE QUALITY ASSURANCE DEPARTMENT WAS IN THE OPERATIONS ORGANIZATION, WAS THE INITIATION OF A DIVISION-WIDE QUALITY IMPROVEMENT PROGRAM. THIS NEW EFFORT IS TIED INTO A CORPORATE AEROSPACE DIVISIONS' OVERALL QUALITY IMPROVEMENT PROGRAM WHICH STARTED IN JULY 1982 AS AN ACTION TAKEN AS A RESULT OF THE DEPARTMENT OF DEFENSE BOTTOM LINE CONFERENCE.

RECOGNIZING THE IMPORTANCE OF THE PROGRAM, AND REALIZING THAT IT SHOULD NOT BE CONSIDERED AS JUST ANOTHER QUALITY ASSURANCE DEPARTMENT PROGRAM, THE DEPUTY GENERAL MANAGER - OPERATIONS ASSUMED PRIMARY RESPONSIBILITY FOR THE PROGRAM AND INSTITUTED THE DIVISION POLICY AND OPERATING PROCEDURES TO CARRY IT OUT.

- DIVISION QUALITY IMPROVEMENT PROGRAM (CONTINUED)

  THE THREE MAJOR ELEMENTS OF A QUALITY IMPROVEMENT PROGRAM HAVE BEEN INCLUDED IN OUR APPROACH - TOP LEVEL MANAGEMENT INVOLVEMENT, ESTABLISHMENT OF MEASURABLE PROGRAM ELEMENTS WITH ANNUAL GOALS AND REPORTING, AND A MASSIVE TRAINING PROGRAM.

  OUR PROGRAM HAS JUST STARTED AND WE ALREADY HAVE SEEN SOME GOOD RESULTS. WITH ITS CONTINUATION AND FURTHER REFINEMENTS, WE EXPECT TO SEE SUSTAINED IMPROVEMENTS IN THE FUTURE.

WITH THESE SEVERAL EXAMPLES OF SOME OF THE INITIATIVES INSTITUTED WHILE QA WAS PART OF THE OPERATIONS DEPARTMENT, AND WITH THE GRADUAL MOLDING OF A MORE INTEGRATED QUALITY ENVIRONMENT IN OPERATIONS, I COULD SEE THAT THIS ORGANIZATIONAL STRUCTURE WAS INDEED WORKABLE, AND THAT IT WAS PROVING ITS EFFECTIVENESS. WE DID HAVE AN IMPROVED AND INTEGRATED QUALITY APPROACH, WITH MUCH BETTER COMMUNICATIONS AND TEAMWORK. BY THE END OF THAT FIRST YEAR I WAS BECOMING A REAL BELIEVER, AND WAS SO CONVINCED THAT I VOLUNTEERED TO TELL YOU ABOUT IT AT THIS FORUM. IT SOUNDED LIKE A PERFECT "BEFORE AND AFTER" SCENARIO.

THEN, SHORTLY AFTER SUBMITTING THE ABSTRACT FOR THIS TOPIC TO NWC/CHINA LAKE, THE GENERAL MANAGER CALLED ANOTHER SPECIAL STAFF MEETING - ON 30 NOVEMBER 1982. AND, YOU KNOW WHAT THAT MEANT. IT SEEMS THAT WITH SOME OF THE DIFFICULTIES AND ORGANIZATIONAL VACANCIES BEING EXPERIENCED AT OUR CONVAIR DIVISION IN SAN DIEGO, CORPORATE HEADQUARTERS MADE A DECISION TO TRANSFER SOME KEY PEOPLE. SO, IT WAS ANNOUNCED ON 30 NOVEMBER, THAT, EFFECTIVE THE NEXT DAY, 1 DECEMBER 1982, THE TWO POMONA DIVISION DEPUTY GENERAL MANAGERS WERE TRANSFERRED TO THE SAN DIEGO DIVISION.

THIS WAS OUR ORGANIZATION CHART, THEN, ON 1 DECEMBER 1982.

MY REACTION, AS HEAD OF THE QUALITY ASSURANCE DEPARTMENT, WAS "WOW! HERE WE GO AGAIN!". ALL MY CONVICTIONS THAT I HAVE JUST DESCRIBED TO YOU IMMEDIATELY BECAME RESERVATIONS ONCE AGAIN. MY PRECEPT THIS MORNING IS THAT THE QUALITY DEPARTMENT CAN OPERATE EFFECTIVELY IN AN OPERATIONS ORGANIZATION AND ENVIRONMENT, PROVIDING THAT THE RIGHT COMBINATION OF INDIVIDUALS ARE IN THE TWO TOP POSITIONS. AND ON 1 DECEMBER LAST YEAR I HAD TO START WORRYING OVER THAT - AND, INCIDENTALLY, START REWRITING MY "BEFORE AND AFTER" SPEECH FOR TODAY INTO A "BEFORE AND AFTER AND HEREAFTER" SPEECH.

FROM 1 DECEMBER LAST YEAR UNTIL 6 JANUARY 1983 WE OPERATED IN LIMBO SOMEWHAT, WITH EVERYONE WHO PREVIOUSLY HAD REPORTED TO THE DEPUTY GENERAL MANAGERS, NOW REPORTING TO THE GENERAL MANAGER ON AN INTERIM BASIS. THAT ARRANGEMENT, IN ITSELF WAS A LITTLE DIFFICULT, WITH 25 PERSONS TRYING TO SHARE THE GENERAL MANAGER'S TIME AND SCHEDULE, AS YOU CAN SEE ON THIS SLIDE.

HOWEVER, AND YOU MAY HAVE ALREADY ANTICIPATED THIS, ON 6 JANUARY 1983, THE GENERAL MANAGER CALLED ANOTHER SPECIAL STAFF MEETING. AND BY NOW, YOU ALL SURELY MUST KNOW WHAT THAT MEANS. A NEW DEPUTY GENERAL MANAGER FOR FINANCE AND ADMINISTRATION WAS APPOINTED, THE DEPUTY GENERAL MANAGER - OPERATIONS POSITION WAS ELIMINATED, AND IN ITS PLACE WE NOW HAVE A VICE PRESIDENT FOR PRODUCTION, EXCEPT THAT THE QUALITY ASSURANCE AND PROCUREMENT DEPARTMENTS HAVE BEEN SEPARATED FROM THAT ORGANIZATION AND NOW REPORT DIRECTLY TO THE GENERAL MANAGER.

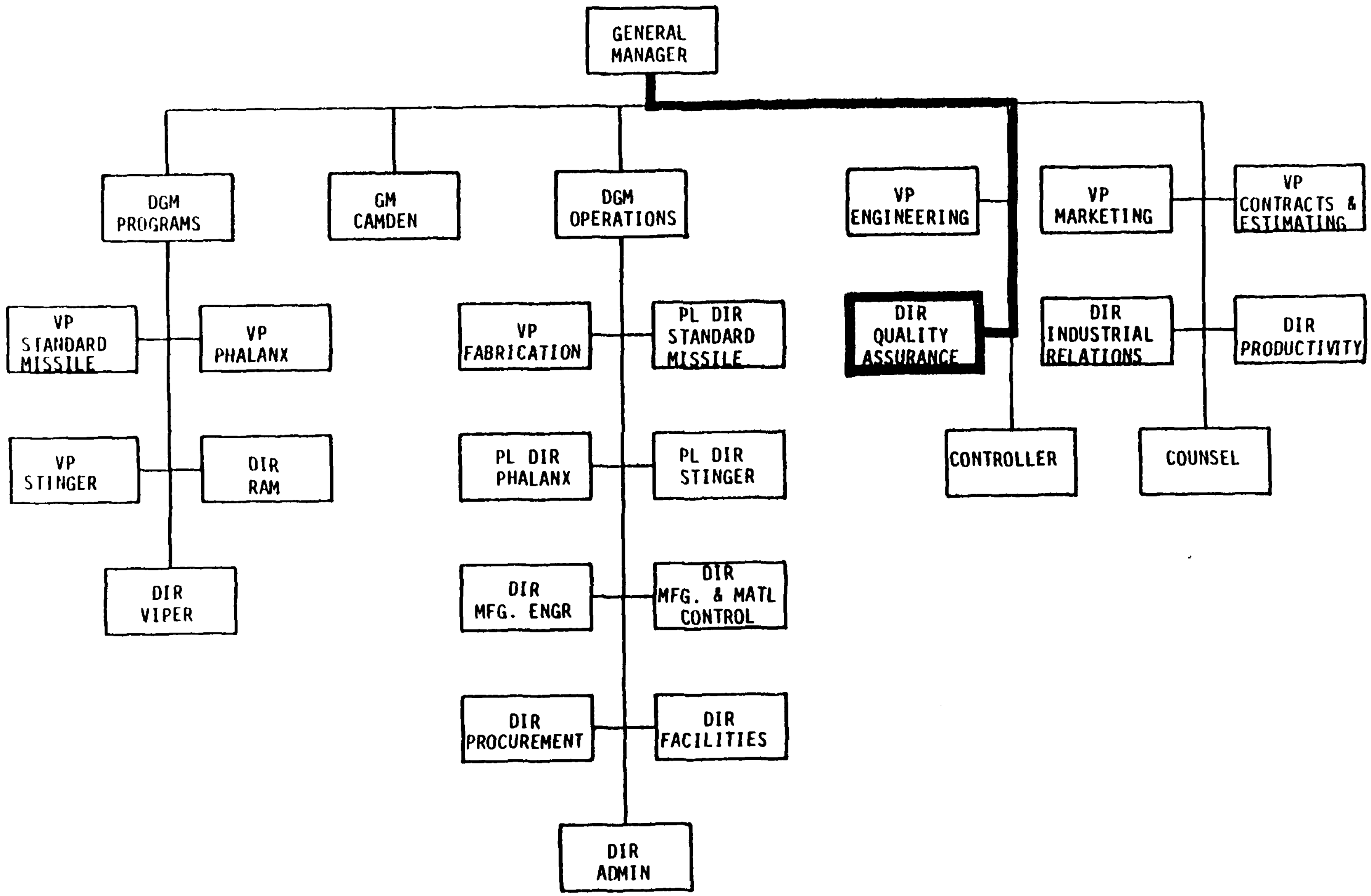
AND SO, THE QA DEPARTMENT AT POMONA HAS COME FULL CIRCLE. AND MY ORIGINAL IDEA TO PRESENT SOME COMMENTS ON THE "BEFORE AND AFTER" ORGANIZATION HAS CHANGED TO A "BEFORE AND AFTER AND HEREAFTER - AND FOREVER MORE!".

WITHOUT THE TIME OR INCLINATION TO REWRITE THIS SPEECH A THIRD TIME, LET ME CLOSE NOW WITH THE CONCLUSION THAT A QUALITY ASSURANCE DEPARTMENT CAN FUNCTION EFFECTIVELY AS PART OF OPERATIONS - IF YOU HAVE THAT HAPPY COMBINATION OF KEY PEOPLE WHO ARE DEDICATED TO QUALITY AND WHO ASSUME THE APPROPRIATE RESPONSIBILITY

OF THEIR POSITION. AND INCIDENTALLY, THAT SAME COMMENT IS RELEVANT TO THE QA DEPARTMENT WITH A REPORTING LINE DIRECT TO THE GENERAL MANAGER.

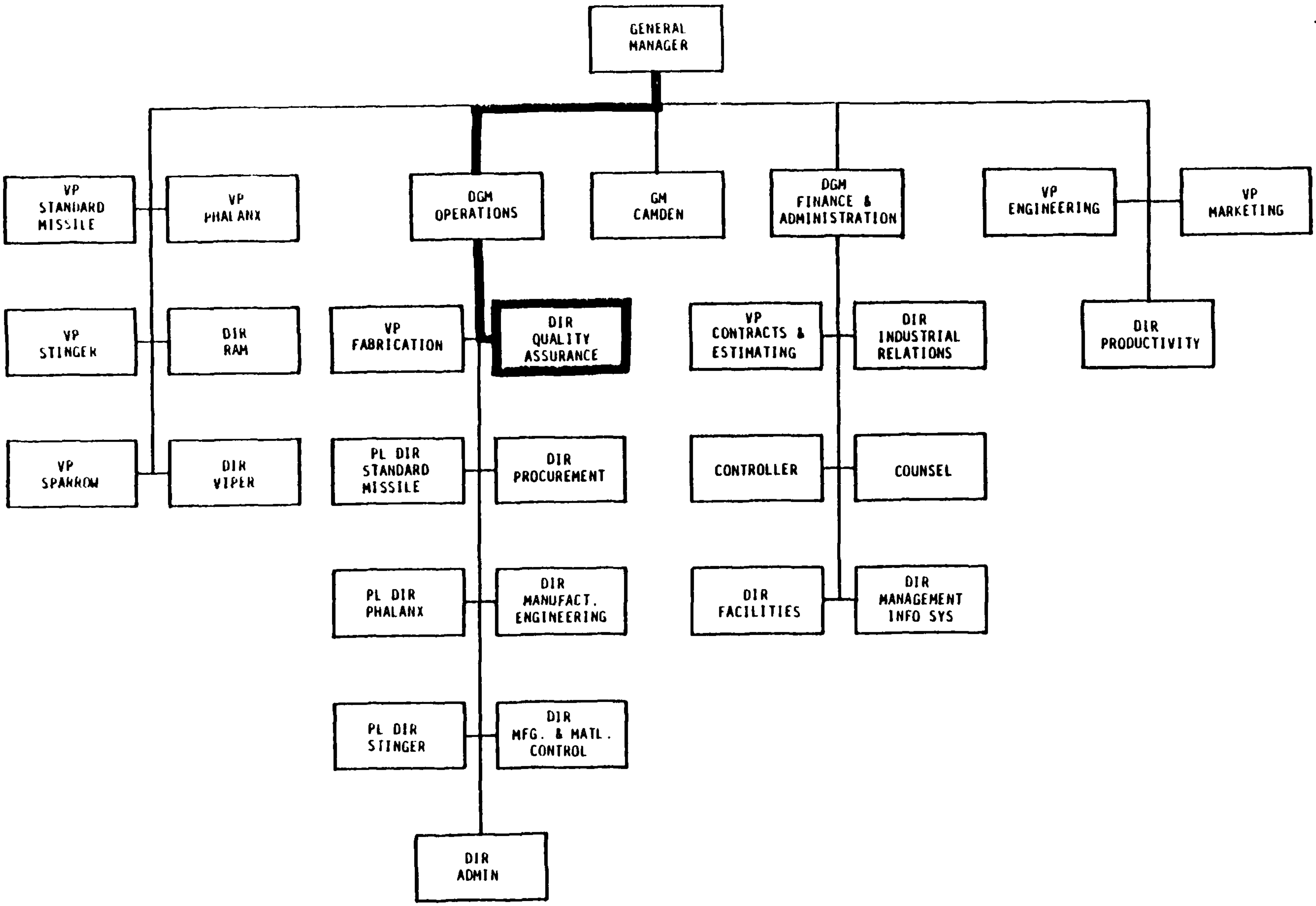
MY EXPERIENCE WORKING IN THE OPERATIONS ORGANIZATION WAS A GOOD ONE, BUT JUST IN CASE ANY OF MY COMMENTS ARE REPEATED TO MY NEW BOSS (THE GENERAL MANAGER) IN THE LATEST ORGANIZATION, I'M SURE I WILL BE EQUALLY HAPPY, OR MORE SO, REPORTING ONCE AGAIN TO THE GENERAL MANAGER.

GENERAL DYNAMICS POMONA DIVISION



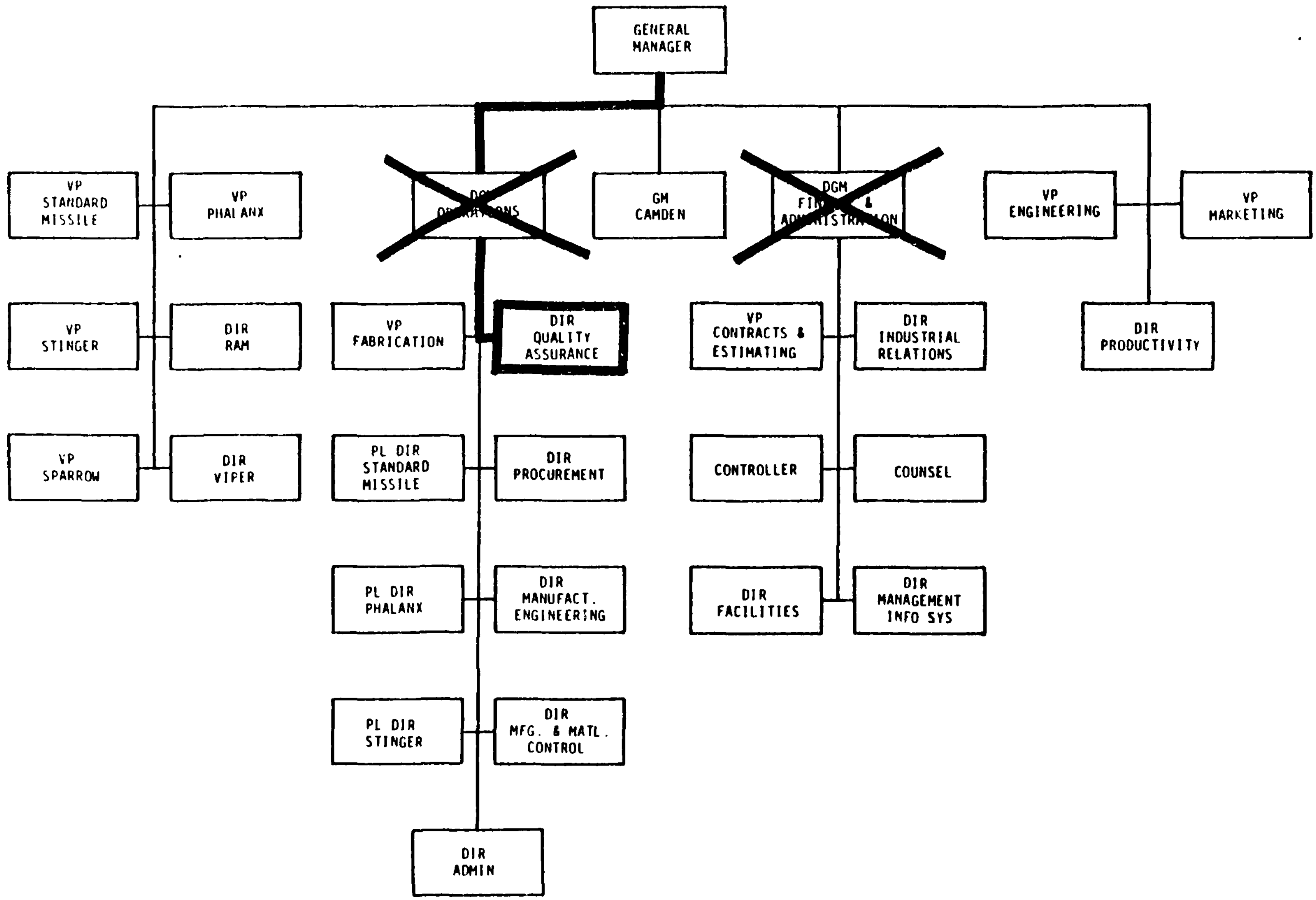
VUGRAPH 1

GENERAL DYNAMICS POMONA DIVISION



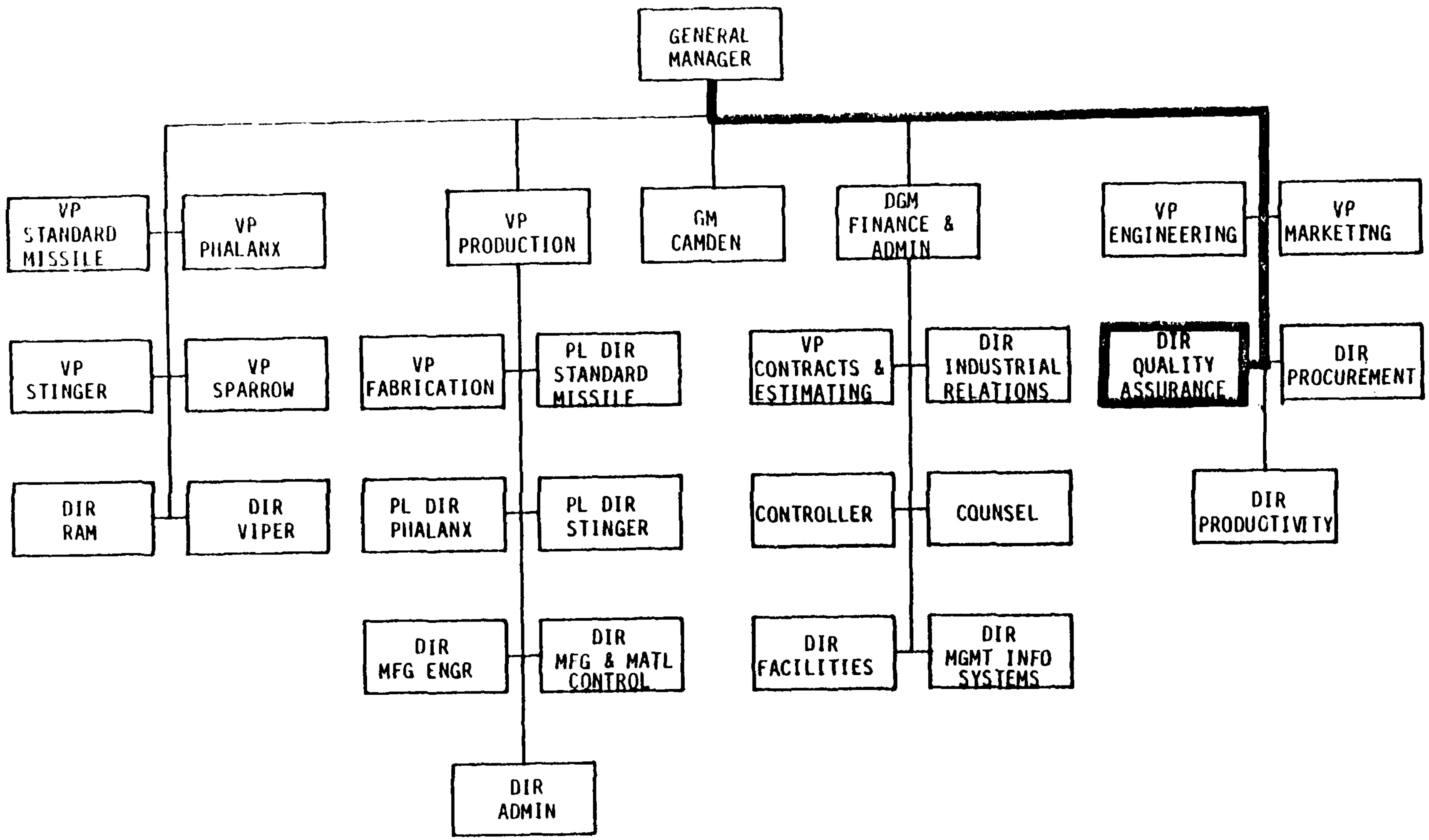
VUGRAPH 2

GENERAL DYNAMICS POMONA DIVISION



VUGRAPH 3

GENERAL DYNAMICS POMONA DIVISION



VUGRAPH 4

DETERMINATION OF RELATIVE ACTIVITY AND POT LIFE OF SOLDERING FLUX USING WETTING BALANCE TECHNIQUES

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EVALUATION OF FLUX ACTIVITY AND POT LIFE·OF USING WETTING BALANCE TECHNIQUES

John Rizzo
Boeing Aerospace Co.
Seattle, WA 98124

Introduction

A large number of different types and brands of soldering fluxes are currently availible on the market, and new fluxes are being introduced every year. To assist in selecting the most suitible flux for a given process, it is desirable to have a comparative method of evaluating the fluxing action, or "activity" of different fluxes. A method has been developed which measures the activity of a variety of different fluxes, regardless of chemical composition. The method consists of a series of wetting balance ("meniscograph") tests on treated copper wire. Testing was conducted on 17 different rosin, organic, and synthetic fluxes. Results were compared with and generally matched flow soldering results. The method was then applied to the determination of pot life of RA flux in a wave applicator. The flux is now replaced before it begins to degrade, which has increased product quality by preventing the use of inadequate flux.

The Wetting Balance Test

The wetting balance (meniscograph) test measures the force which is exerted by molten solder on an immersed specimen. A test is commenced when a solder pot is raised to about 3mm above the bottom of a fluxed specimen, which is suspended from a transducer. A plot of the force versus time can be recorded during a 10 second test (figure 1). The force initially drops as the specimen is immersed in solder. This is the bouyancy force. When the solder starts to wet the metal sample, the force is reversed and the curve starts to rise. The rate of rise of the curve is a function of the activity of the flux used. The curve typically rises to a maximum force and levels off. The spike at the end of the curve is due to the withdrawal of the test specimen from the solder.

The test apparatus (the Ersin Multicore Universal Solderability Tester) has a microprocessor that calculates the wetting time, which is defined here as the time it takes the wetting force to reach 63% of the maximum. The data for the rising portion of the force- time curve approximates an exponential form, and is fit to the following equation:

$$g=F(1-e^{-t/s})$$

where t=time
g=wetting force at time t
F=maximum wetting force
s=time constant (wetting time)

S is the time from the start of wetting for g to rise to 0.632F, and is therefore a measure of the speed of wetting.

A correlation factor calculated by the unit is a measure of the reliability of the data which relates how well actual data points fit the theoretical curve.

Wetting of a metal by solder is strongely influenced by very small changes on the surface, even on the molecular level. Test results cannot be evaluated individually, but must be considered statistically (batch-wise). The larger the batch, the more reliable and accurate the data. Typical batch sizes are 25 to 50 tests. One method of statistically evaluating wetting balance data is to plot the wetting times on a normal logorithmic distribution curve, called a probability curve (figure 2) On one axis the wetting times are plotted in order of magnitude. Probability is plotted on the abscissa (0.01% to 99.99%) as values for "a" given by:

$$a=100(2n-1)/2N$$

where N= test batch size
n= rank of wetting time

For a batch size of 50, the smallest wetting time is then plotted on the 1% line, the next largest on the 3% line, and so on until the longest wetting time is plotted on the 99% line. The abscissa value for a given ordinate is the likelyhood that a test will yield a wetting time which will fall below that particular value. It is also the percentage of wetting times of the tested flux likely to fall below the given value.

If the test specimens are fairly uniform, the points will fall in an approximately straight line. This linearity is an indication of a homogeneous population with a normal distribution around a median value. This median is used to represent the wetting time of the batch of tests. The median wetting time has been found more representative than the average, which is greatly affected by anomalies with very large wetting times. The median wetting time is then used to represent the activity of the tested flux.

Development of the Flux Evaluation Procedure

The evaluation of flux activity using a wetting balance requires a standard test specimen to be used for all tests. The specimen should be a uniform metal surface which can be acted upon by the normal fluxing mechnisms, and should be fairly small in size so that heat transfer effects are minimal. The metal surface should

also be sensitive to fluxes of varying activities, and should yield wetting times that fall within a range which is useful for evaluation purposes. Noise (interference) levels of the tests increase with increasing wetting times, rendering long wetting times unreliable. On the other hand, wetting times clustered near 0.00 are not useful for comparative evaluation.

Kester 1585M RA flux (used in-house for military flow soldering) was used for evaluating metal test specimens for suitability to flux testing. Wetting balance tests were conducted with wires, ribbons, and coupons of various sizes. Surfaces made of copper, gold, solder and kovar were tested, methods of preparation were studied, and probability curves were prepared from wetting balance data and checked for linearity. Chemically treated copper wire (0.032) was found to be most suitable for flux evaluation. Gold was not sensitive to different fluxes, solder yielded scattered data, and kovar yielded wetting times that were too small.

The selected sample preparation is derived from several methods found in the literature (ref. 3,4,5):

1. Vapor degrease, Freon TES, 1 minute;
2. Etch, Ammonium persulphate , 2.5 minutes;
3. Rinse, 0.2% (volume) sulphuric acid rinse, 2-3 seconds,
4. Rinse, acetone, 2-5 seconds;
5. Bake, circulating air, 140 C, 1 hour.

The etch is employed to expose the bare copper surface, and a bake is used to put on and even oxide layer. The purpose of the acid rinse is to prevent the copper from reacting with dissolved oxygen and hydroxyl ions in water, which causes the wetting times to be affected by small variations in rinsing time. (Ref,4,5.) Acidified water prevents this problem by reducing the stability of Cu_2O and CuO to the point where they dissociate upon formation.

The effectiveness of this flux evaluation method was tested by conducting 50 wetting balance tests each on the RMA, RA, and OA fluxes used in-house, which are known to have respectively increasing relative activities. The probability curves plotted for these three fluxes (figure 2) were linear and of similar slope, indicating a high confidence level in the data. Wetting balance values fell into ranges which corresponded to the relative activities known from experience. Force-time curves produced a slow, gradual force rise for RMA, a steeper rise with a rounded leveling off section for the RA, and an almost vertical force rise with a sharp transition to the maximum force plateau for OA.

Results of Evaluation of Fluxes

17 fluxes were tested in batches of 50 tests per flux. Flux types included milspec and non-milspec qualified Rosin Activated (RA) Super Rosin Activated, Organic Acid (OA), non-acid organic, and inorganic (synthetic). Each flux was compared in activity to a "standard" milspec RA flux (Kester 1585M), used in-house for flow soldering. Tests were conducted with the standard on every day a new flux was tested. Fresh copper wire was prepared each day of testing.

To normalize the data and eliminate the effect of daily differences in the sample oxide coatings, the median wetting time for each flux was divided by the median wetting time found for the standard flux on the same day. The resulting ratio indicates a hotter flux than the standard RA if it is less than 1.0. The fluxes were then ranked according to activity ratio, which is a measure of the activity (figure 4).

Several double-sided printed circuit boards were mounted with copper wire prepared in the same manner as for the wetting balance testing. The boards were then flow soldered using several of the tested fluxes. The fluxes were then ranked for activity based on solder joint formation and the travel of solder up the copper wire. Generally, the rank of activity according to flow soldring agreed with that obtained from wetting times and force-time curves.

Based on activity, the fluxes generally fell into families of similar types. The four OA fluxes were the most active fluxes evaluated. The organic non-acid also showed high activity. The non-milspec compliant RA fluxes were next in activity, followed by the milspec compliant rosins. The RMA flux was the least active flux tested. The results of the testing (figure 4) reveal how each flux used in house compares in activity with other fluxes in that particular family. It also shows how active "oddball" fluxes (ie., inorganic and organic non-acid) are in relation to more standard flux types.

RA Flux Pot Life Study

Over a period of time the RA flux in a 25 gallon wave applicator begins to loose activity and become sticky and difficult to remove with normal cleaning procedures. This results in increased solder defects and the need to clean soldered assemblies several times. The time the flux takes in the wave applicator to begin lossing activity was determained using the same wetting balance method described above. It was discovered that flux deterioration in the wave applicator was a function of calander time rather than usage or running time.

A sample was taken from the wave applicator three times a week and tested in the same manner as the fluxes mentioned above. Copper wire was freshly prepared and new RA flux (kept in a sealed container) was tested as a control on each day a pot

sample was drawn. The median wetting time of the pot sample was divided by that of the control sample.

Figure 5 is a plot of the activity ratio vs. time for a 72 day period. The activity ratio for each day was evenly distributed around 1.0 (average 0.97) until the 54th day, when the ratio started climbing higher (average 1.45). Flow soldering defects also started increasing at about this time. The flux was later replaced and the tests repeated. Once again, the flux ratio started to increase at about 54 days, and the average wetting ratios before and after this point (1.08 and 1.41) were similar to those from the first run. The working time of the wave applicator for the two data runs at the time of activity decay was 26.5 and 18.2, respectively , which shows that the activity decay is more a function of calander time. The data for both runs indicates a continueing decreasing trend in activity.

Conclusion

Flux activity, although not the sole consideration when choosing a soldering flux, is one of the more important properties to consider. The method described here can be used to measure the comparative activity of fluxes provided that testing is conducted with sufficiently large batches and is evaluated statistically. Use of etched and baked copper wire yields wetting time data which is consistant and useful for flux evaluation. This method eliminates the need to experiment with fluxes on the producton line. In addition to the testing of new materials, the wetting balance method can be used to determine the time when flux begins to loss its activity. This knowledge prevents use of flux which has degraded in quality.

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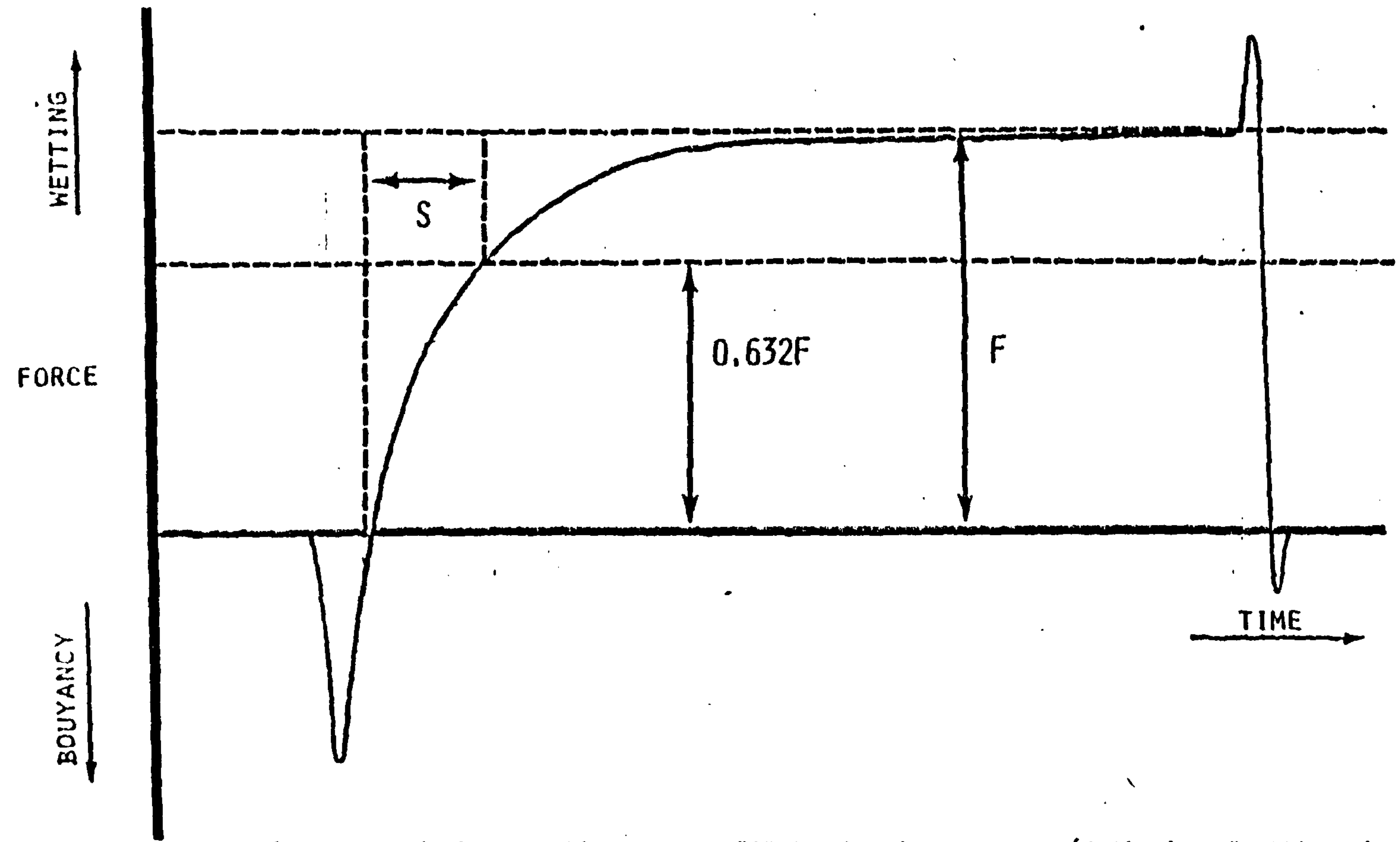

Figure 1: Theoretical force-time curve. "S" is the time constant (defined as "wetting time") calculated by microprocessor.

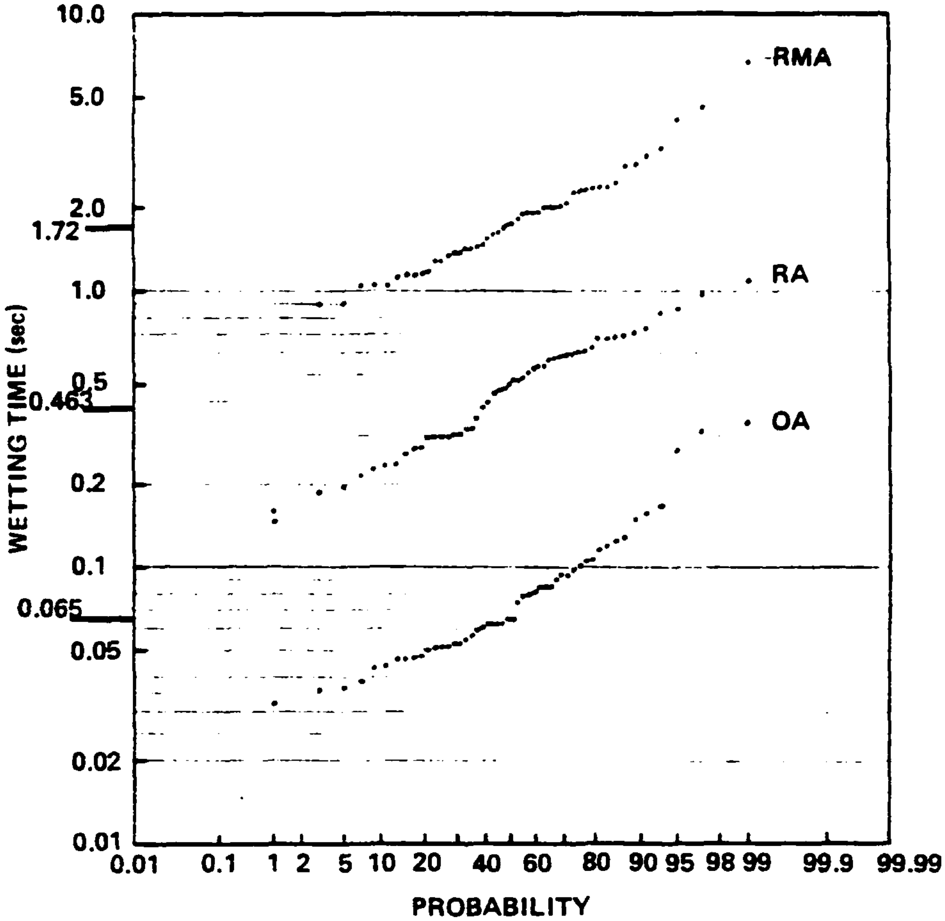

Figure 2: Probability curves for three types of flux. 50 wetting times for each flux are plotted on log-log coordinates. The median value (50% probability) for each batch is given on the left, and is used to represent the activity of each flux.

RMA

RA

OA

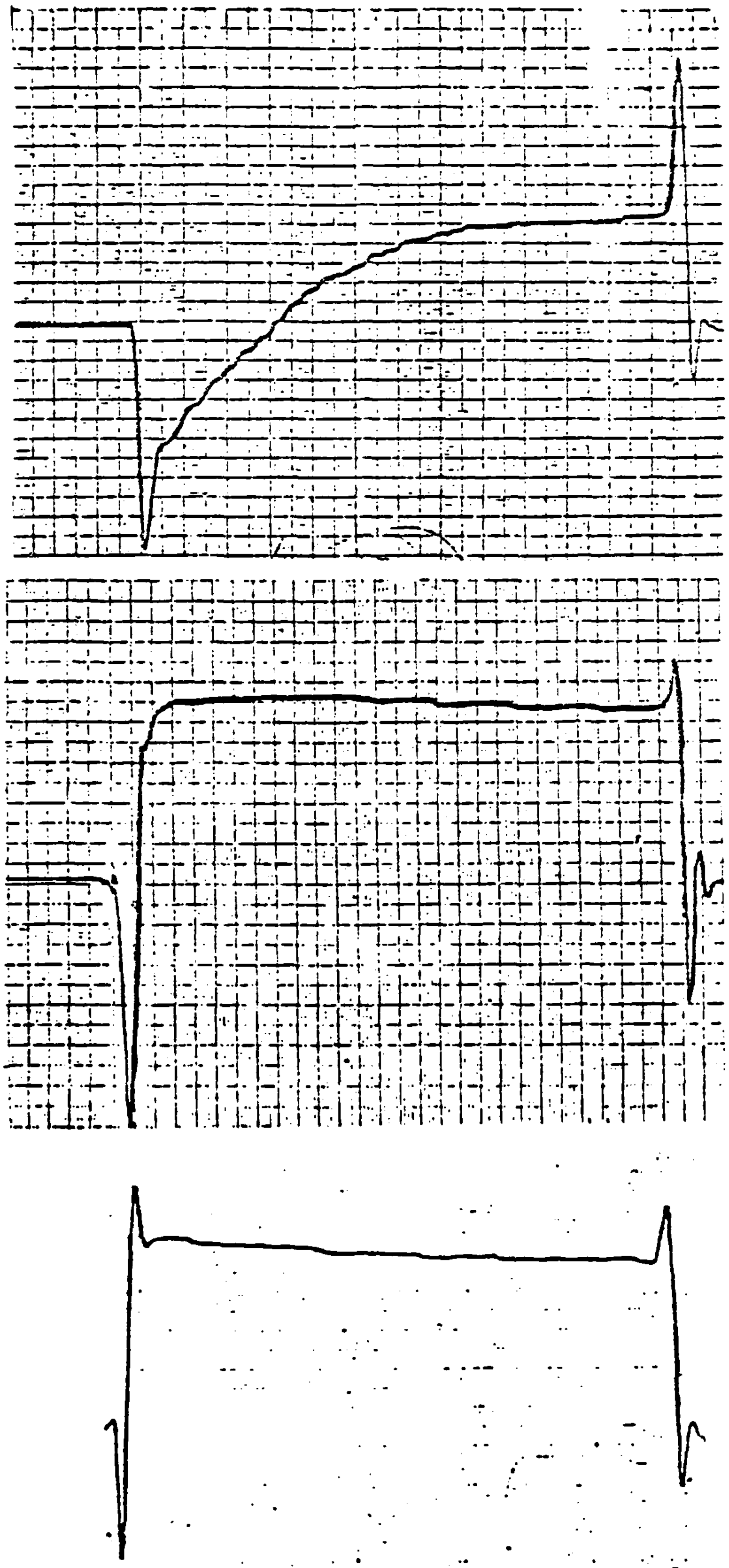

Figure3: Force-time curves for RMA, RA, and OA flux. Less active fluxes yield a smoother, more gradual rise in force. More active fluxes yield sharp and steep rises in force. The spike at the top of the force rise on the OA curve is due to system inertia, and is indicative of a highly active flux.

BOEING ELECTRONICS SUPPORT DIVISION

RANK BY ACTIVITY RATIO	FLUX*	TYPE	MIL-P-14256	ACTIVITY RATIO= $\frac{\text{MEDIAN WETTING TIME}_X}{\text{MEDIAN WETTING TIME}_{F-3}}$	RANK FROM FORCE-TIME CURVES	RANK FROM FLOW SOLDER
1	A-1	OA		.099/.468 = .211	1	1
2	B-1	OA		.062/.262 = .237	1	2
3	C	OA		.119/.468 = .254	1	3
4	D(HOUSE OA)			.065/.246 = .264	1	-
5	E-1	RA		.066/.180 = .366	1	-
6	F-1	NON-ACID ORGANIC		.087/.186 = .468	1	5
7	B-2	SRA		.100/.180 = .555	1	4
8	F-2(HOUSE RA,NON_MIL)			.059/.087 = .678	-	-
9	E-2	RA	YES	.155/.204 = .759	-	6
10	F-3(HOUSE RA, MIL-SPEC)		YES	1.00	2	7
11	G-1	RA	YES	.229/.193 = 1.187	-	-
12	F-4	RA	YES	.306/.193 = 1.585	-	-
13	B-3	RA	YES	.318/.186 = 1.710	3	-
14	H	INORGANIC		.470/.262 = 1.793	-	-
15	G-2	RA	YES	.368/.193 = 1.907	-	-
16	A-2	RA	YES	.590/.186 = 3.172	4	-
17	F-5(HOUSE RMA,MIL)		YES	1.72/.180 = 9.56	5	-

*ACH LETTER DESIGNATES A MANUFACTURER

Figure 4: Results of the comparative flux study.

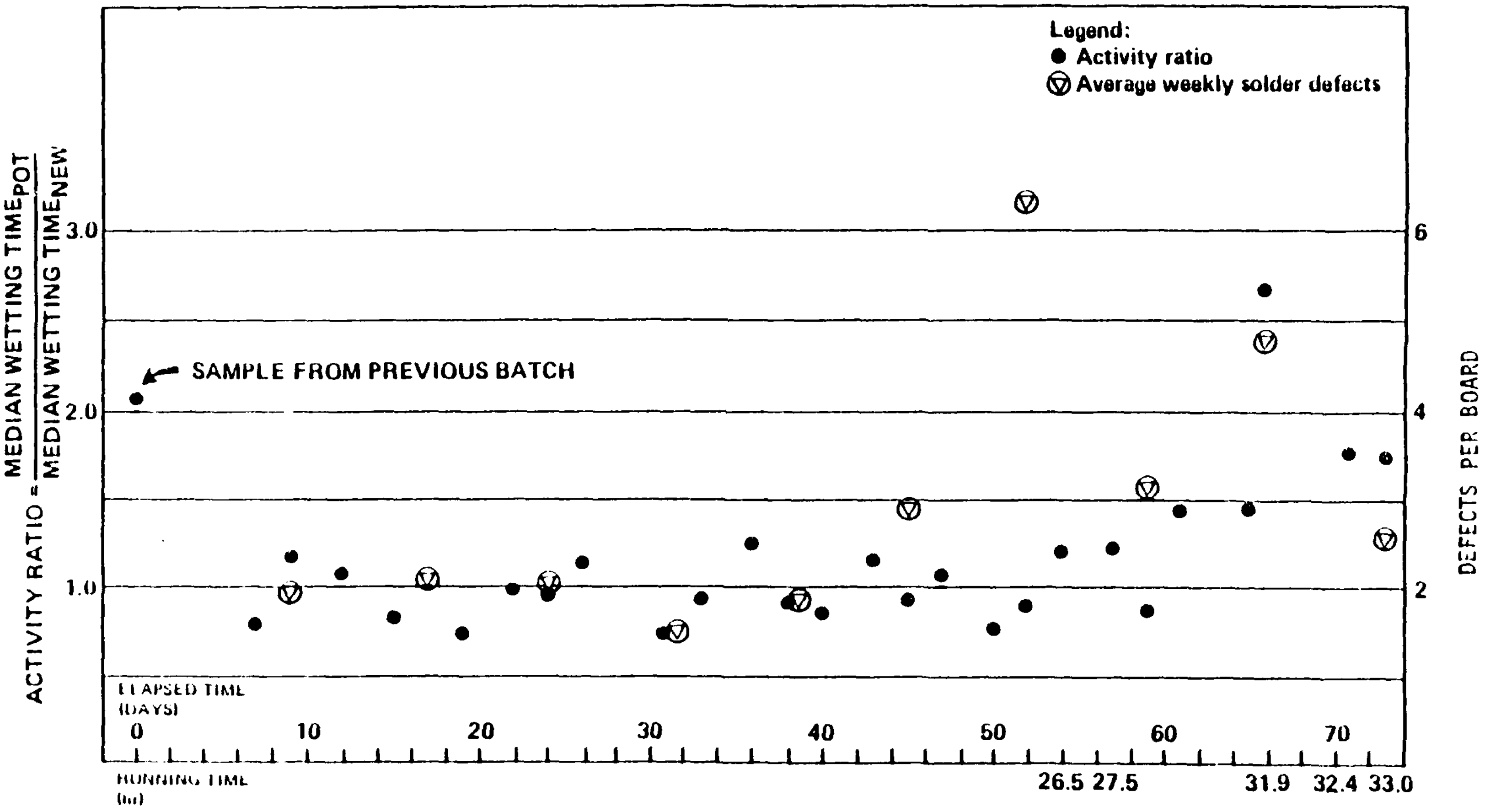

Figure 5: Pot life study- Flux activity of RA flux and average solder defects over a 10 week period.

SOLDER TRAINING

AT HUGHES AIRCRAFT COMPANY

TUCSON MANUFACTURING DIVISION

GWEN E. MARKHAM
Technical Supervisor
Process Engineering Department

5

SECTION I

High quality, high technology hardware begins with proper training. The Tucson Manufacturing Division of Hughes Aircraft Company is a major defense contractor which employs over 800 skilled electronic assemblers. Training of all employees is an on-going process, beginning their first day on the job. In fact, only applicants with previous experience in electronic assembly are considered for employment as assemblers.

Solder training involves more than simply Mil-Spec. certification. Many missile programs are produced simultaneously at one facility for the Army, Navy, Air Force and Marines. Each program has a specific set of solder and assembly requirements, thus the employees must know these specific to the hardware they assemble. Many members of the engineering and supervisory staff also need a working knowledge of solder requirements. There is such a diversity of hardware within the facility that it sometimes becomes necessary to develop a special course for one type of problem hardware.

Utilizing a common training board, we have developed several courses specific to the needs of particular groups of people. We have also developed special hardware for courses such as a rework course, and a precision assembler course.

The following is a list of standard courses that are taught on a periodic basis depending on need. Detailed descriptions of these courses may be found in Section II of this paper.

A. Basic Mil-S-45743E certification course (40 hours minimum) - taught to all assembly operators.

*B. Mil-S-45743E recertification (20 hours minimum) - audit failure, leave of absence.

*C. WS 6536C (16 hours minimum) - employees who work only to this specification.

*D. Rework (20 hours minimum) - operators of a high labor grade who rework hardware.

*E Inspector Learner (24 hours minimum) - operators promoted to inspector.

*F. Precision Assembler (24 hours minimum) - operators of a high labor grade who build difficult assemblies.

G. Supervisor (40 hours minimum) - assembly supervisors responsible for soldered assemblies.

H. Engineer (40 hours minimum) - Product Assurance and Assembly Engineers with a need to understand solder quality.

Three major departments have integral functions in administration of the training programs. There is a divisional directive which clearly defines the departmental responsibilities and relationships. All personnel, including instructors, Product Assurance Engineers and Process Engineers who are involved in solder certification are certified Category C Instructors/Examiners per the requirements of Mil-S-45743E or WS 6536D.

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*Student must be certified to Mil-S-45743E before taking this course.

The Process Engineering department is primarily responsible for development of courses and curriculum. It is this department which insures that course content complies with the specifications. Process Engineering interfaces daily with the assembly departments, enabling the Process Engineers to design courses applicable to the assembly operations. Another function of the Process Engineers is to evaluate workmanship samples after students have completed the course. This assures that consistency of instruction exists, and all major parts of the course are being properly taught.

The Product Assurance department conducts the semiannual audit of every certified operator within the facility. This department maintains the records on eye exams and latest certification records. All records are kept by computer, and updated daily. Product Assurance is also responsible for workmanship sample evaluation with Process Engineering. In this manner, the two departments are able to maintain the quality and consistency of instruction.

The Human Resources and Administration department maintains the personnel and facilities to conduct the training program. They employ the instructors, procure the materials, schedule the courses and maintain the permanent files on certification of all operators. The instructors perform the initial grading of workmanship samples which are then provided to the Process Engineering and Product Assurance departments.

The training facility is a modern, clean area separated from the assembly areas of the factory. The training room contains 24 work stations equipped with lights, soldering irons, tool kits, grounding apparatus and component

kits. The room is modular and may be divided to accommodate classes of 6, 18, or 24 employees. This flexibility allows two courses to be conducted at the same time. Each instructor conducts a class of not more than 6 students. This assures that each student receives quality instruction.

The basic circuit board used for the majority of the courses is a 6" x 8" double-sided epoxy board. It is fabricated within our PWB fabrication facility as are all our production circuit boards. The board has bifurcated and turret terminals, and ground planes on it. This gives the student practice with several types of assembly challenges.

Components and wires for the course are procured from a variety of sources. Some components come from electrical failures in receiving inspection. Others are bought "blank" or scrap from component vendors. Others come from production surplus, and yet another group is bought as real functioning components from vendors. Most wire is production surplus. The objective in procuring components is twofold. Components must be solderable, and we try to purchase them in the most economical fashion.

The Missile Systems Group of Hughes Aircraft Company considers training of the utmost importance. Assembly operators must be able to solder any hardware, from simple double-sided boards, to 18 layer polyimide multilayers with thousands of connections on each board. The structure of our labor union results in a large amount of employee movement from one program to another. We have found that the best way to accommodate these special circumstances is to train intensively at the start of an employee's career.

We are confident that with proper instruction and skill development, all assembly operators are qualified for any job assignment in the assembler occupation.

SECTION II
COURSE DESCRIPTIONS

A. Basic Soldering

The first course a new electronic assembler will be required to take is Basic Soldering (40 hours minimum). This course is designed to meet the requirements of Mil-S-45743E. It is a very intensive course consisting of a training board and wired terminals. Most new employees need at least 60 hours to complete the course (see Figure 1).

The training board is a 6" x 8" double-sided epoxy circuit board with terminals and ground planes. There are 350 soldered connections and 25 wired terminals on the board. Students are taught assembly techniques, component marking, polarity, assembly planning, simple wire routing, and proper use of assembly tools. Some of the components on the training board are axial lead resistors, capacitors and diodes, transistors, IC's, DIP's, and stand-off resistors and capacitors. Students also install buss wires (sleeved and unsleeved), shrink sleeving around components, and attach axial lead components to bifurcated and turret terminals. A major portion of the training board consists of the construction of a ten wire harness.

The student is also required to submit 8 wired terminal samples. There are single and double wires soldered to hook, turret, birfurcated, and cup terminals.

The final segment of the course is a 25 question, multiple choice exam. Failure of the written exam or failure of the workmanship portion of the class results in failure of the course.

This course is usually given only once to an employee. Failure of the course either results in disqualification from the occupation, or in some cases, termination of employment.

B. Recertification

Any employee who fails the semiannual audit, or whose performance in assembly is judged to be substandard must complete this course. The course is similar in content to the basic course with a few significant changes.

The same double-sided board is used. There are 250 soldered connections and an 8 wire harness. There are also wired terminal samples submitted (see Figure 2).

This course must be completed in less than 24 hours of instruction. An employee who is willing to follow instructions and work at a steady pace should be able to complete the course in this time frame. Remember, an employee in this course has already had a minimum of 40 hours of instruction.

C. WS 6536C

This course is an example of courses designed to accommodate specification differences as they apply to different programs. The main points covered are wire wraps and some stress relief options. We have also included as part of the workmanship sample some of the difficult techniques used in assembly of this program's hardware. An employee enrolled in this course has been previously certified to Mil-S-45743E (see Figure 3).

D. Rework

This course was designed to teach the techniques of component replacement to a high labor grade of solder operator. The circuit board used for the component replacement segment is a polyimide multilayer. The employee must assemble, disassemble, and reassemble the sample with no damage to the circuit board and components. During this course the student is taught the operation of several types of solder removal equipment and use of many tools and techniques helpful in successful component removal (see Figure 4).

E. Inspector/Learner

This course was designed to prepare an employee for the inspection occupation. They are taught solder inspection criteria utilizing a variety of hardware from throughout the facility. This course also involves inspection procedures not specific to soldering.

F. Precision Assembler

This course was designed to simulate some difficult assembly problems including hardware interference, fine wire soldering, and soldering of small connector pins. Operators who pass this course are qualified for a high labor grade and are certified as precision assemblers.

G. Supervisor

Assembly supervisors responsible for soldered hardware need to understand the tools, quality criteria, and problems associated with soldering. This course was designed in 2 segments to teach those items to supervision.

The hands-on soldering segment again utilizes the double-sided training board. The course teaches installation of most common components, and some simple wiring (see Figure 5).

The second segment of the course is conducted by engineers and consists of instruction on the operation of most assembly equipment. Some of the equipment included is component sequencers, automatic insertion, wire cutting, marking, and wave soldering equipment.

H. Engineer

Product Assurance Engineers and Assembly Engineers are typical of those members of the technical staff who require a working knowledge of soldering. This course is structured similarly to the supervisor's course with some differences. Because there are several programs produced concurrently, there was a need for the engineers to understand the governing specifications and their impact. The second segment of the course addresses these specifications and their relationship to the job function of each engineer.

The workmanship sample is the same one used in the supervisors course. This portion of the course requires approximately 20 hours to complete (see Figure 5).

The second segment of the course is conducted by a Process Engineer (Category C Instructor/Examiner) and consists of 20 hours of lecture and discussion on the solder specifications.

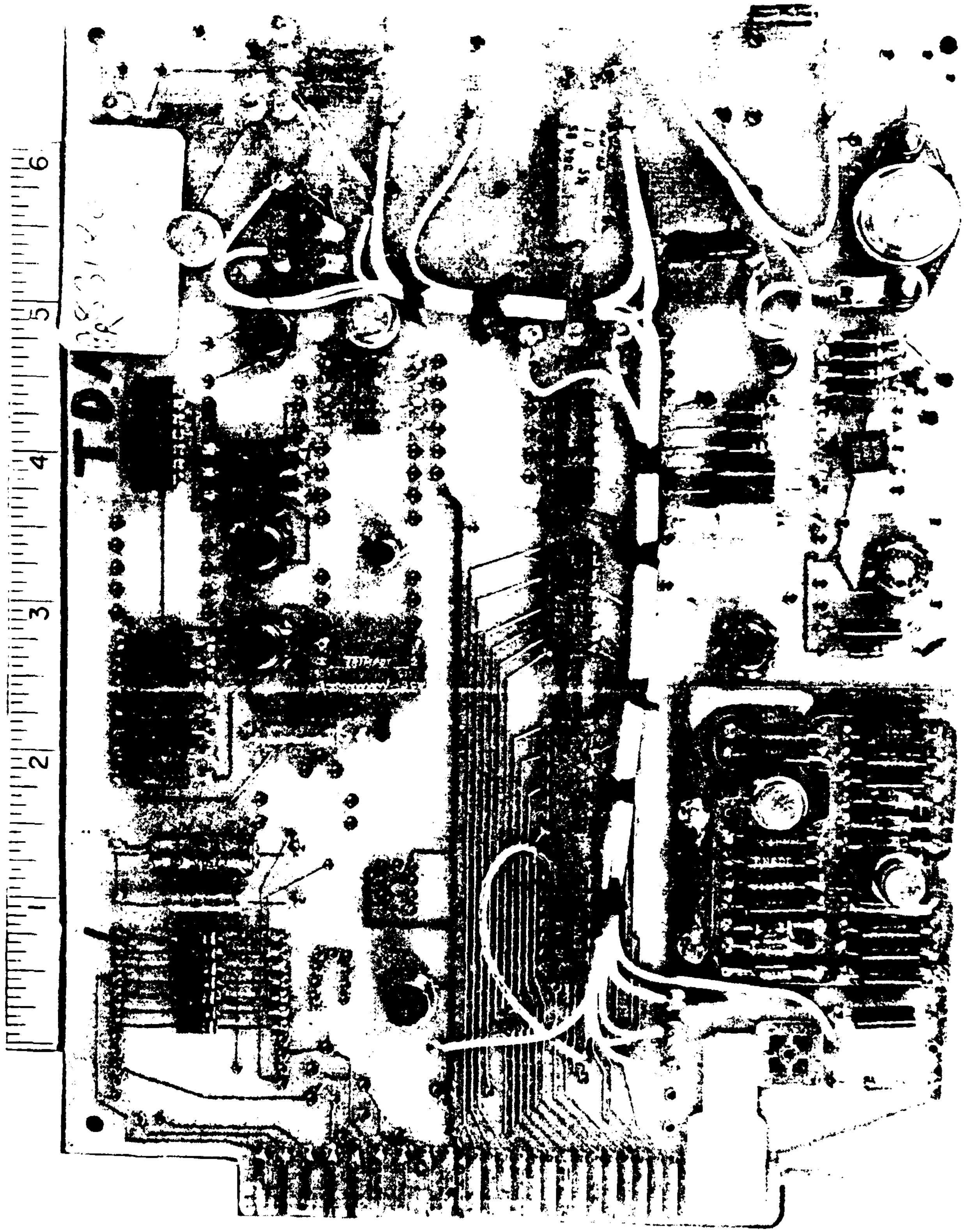


FIGURE 1

BASIC SOLDERING

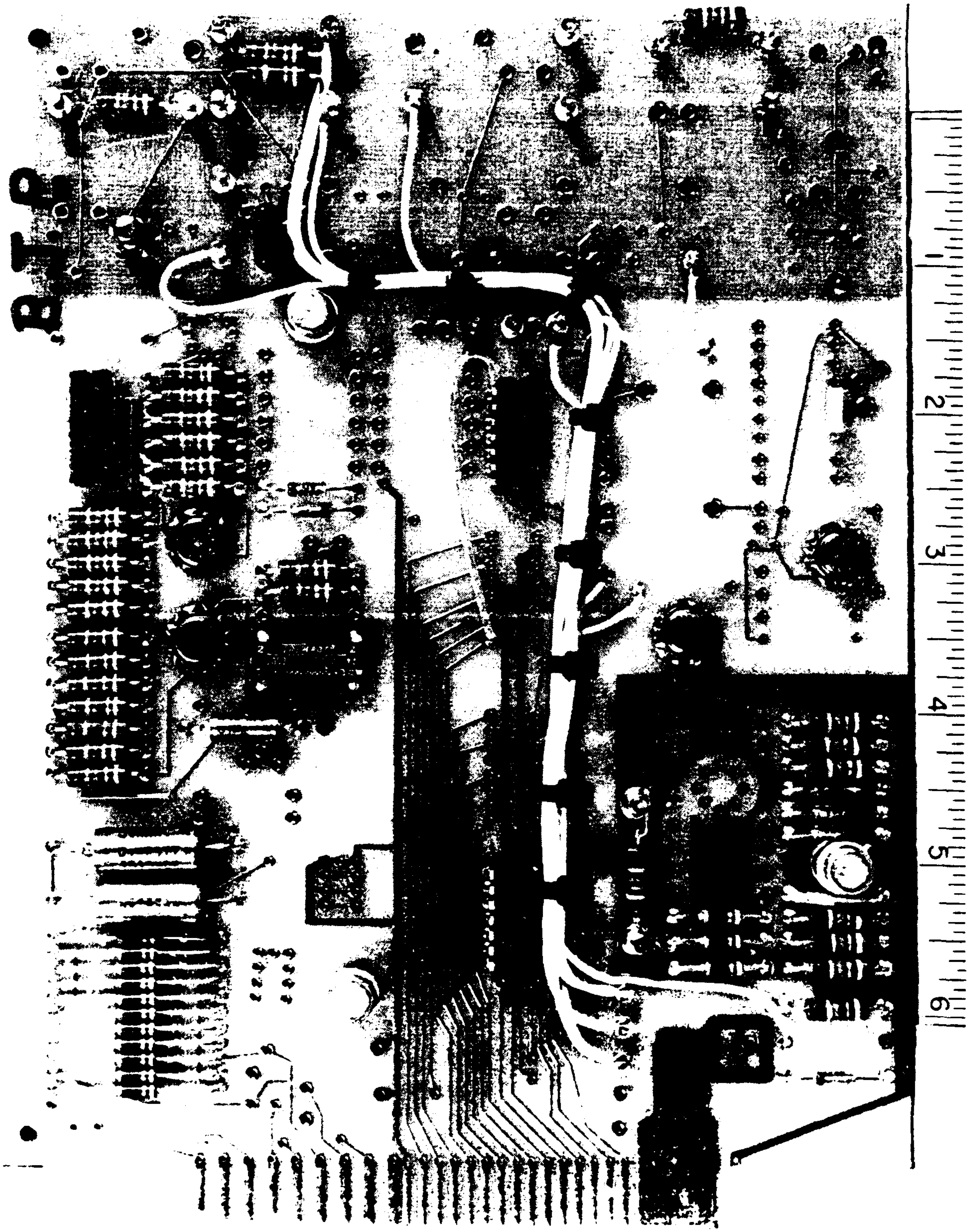


FIGURE 2

SOLDER RECERTIFICATION

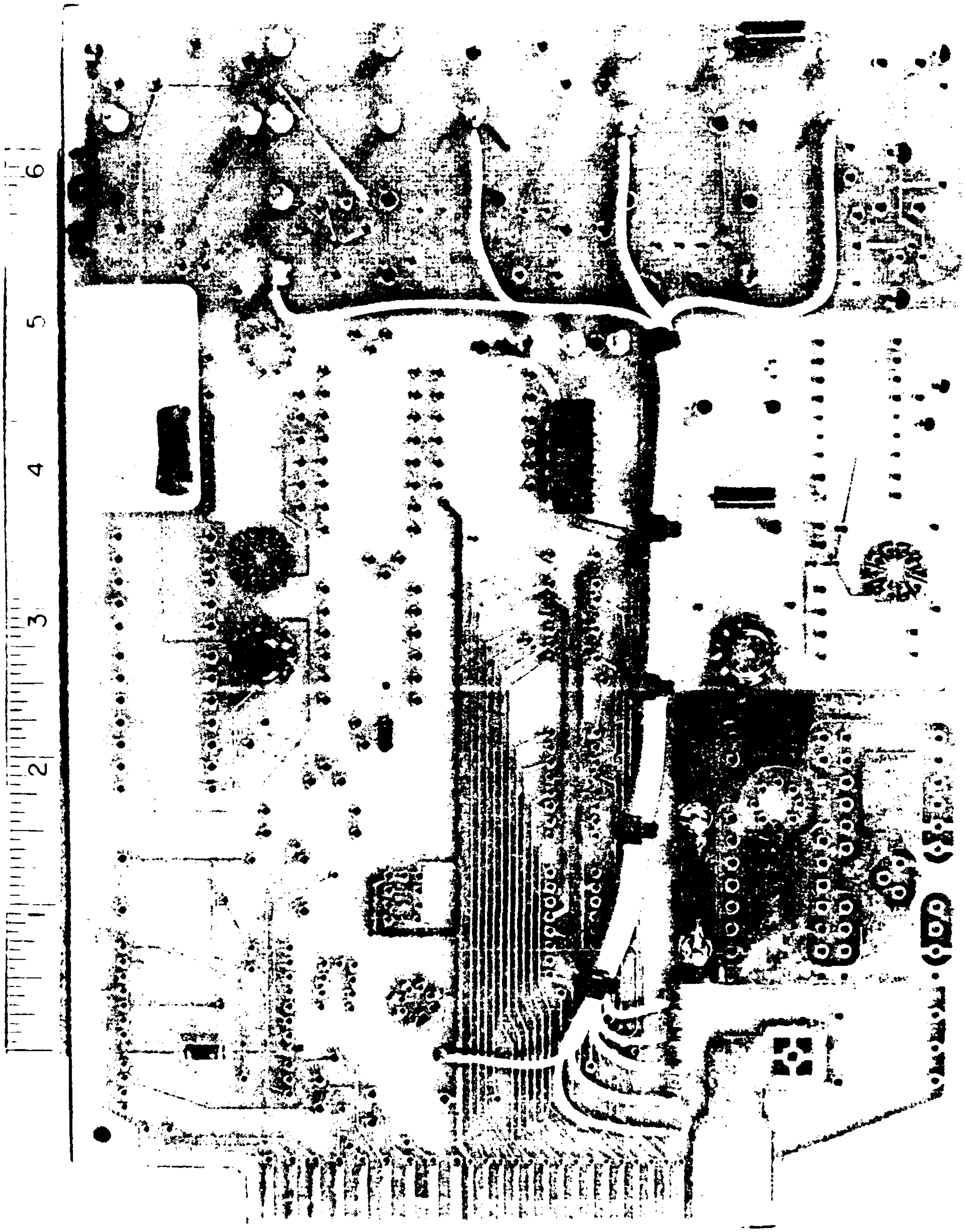


FIGURE 3

WS 65360

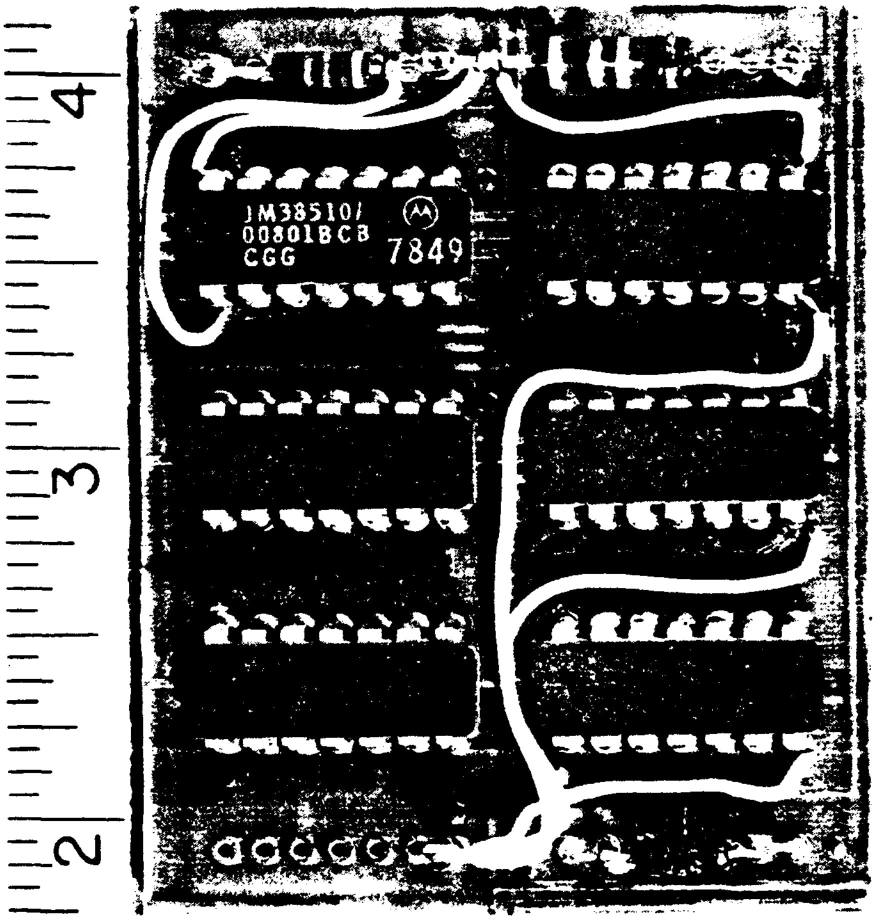


FIGURE 4

REWORK

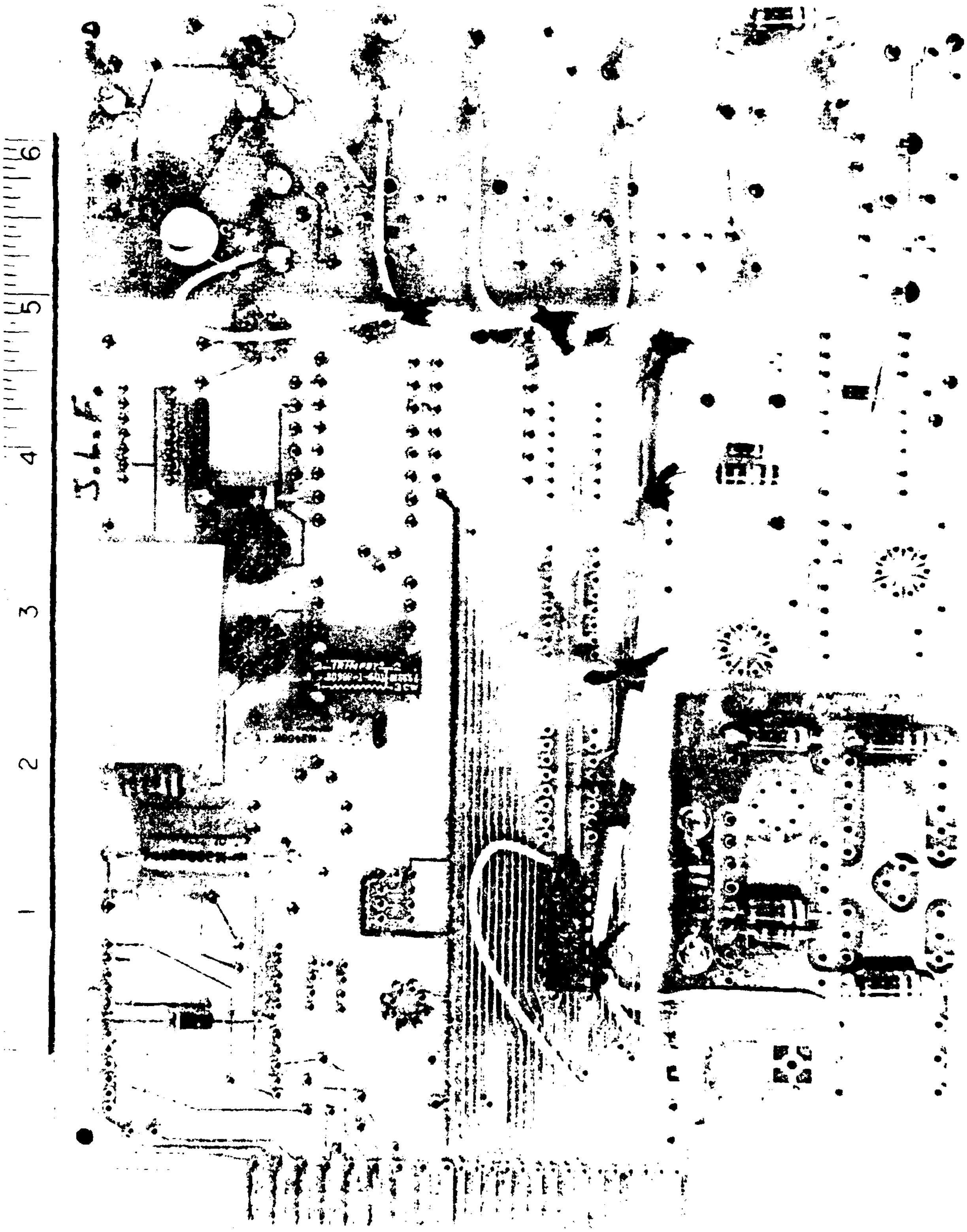


FIGURE 5

SUPERVISOR & TUNNEL

WAVE SOLDER AUDIT SYSTEM-A TOOL FOR PROCESS CONTROL

BY

T. M. Wurzburger

SANTA BARBARA RESEARCH CENTER
A Subsidiary of Hughes Aircraft Company
Goleta, California

Presented February, 1983
Seventh Annual Solder Technology Seminar
Naval Weapons Center
China Lake, California

TABLE OF CONTENTS

I. ABSTRACT

Printed Wiring Boards (PWB's) are loaded with components, wave (flow) soldered and inspected. Finally, the customer (Navy) performs an audit of each Lot of completed Circuit Card Assemblies. This audit is the mandatory customer inspection (MCI) point.

During the manufacture of the Circuit Card Assemblies, immediately following wave solder, a pre-production audit is performed. Following this is an inspection of all Circuit Card Assemblies for all characteristics. Next, is an in circuit component analysis (Zehntel Test), followed by functional (Powered-up) test. Last is final inspection followed by mandatory customer inspection. The inspection traveler is the input document for both initial and final inspection from which the yield chart and computer printout are derived. Corrective action is initiated, if defect rate exceeds one percent of the total possible defects.

II INTRODUCTION

This paper will concentrate primarily on steps 9. through 15. (Figure 1.). Of these steps, nos. 9, 11, 12, 13, 14 are Quality Assurance functions, with the remaining ones Manufacturing, except for the final step, MCI, which is performed on an audit basis by Government Personnel. Input documents for the computer, and yield charts are derived from the inspection travelers (Figure 2 and 3), Figure 2 for initial and Figure 3 for final inspection. Appendix A. (pp.12-14) describes information to be printed out, algorithm, record indentification, defect indentifcation, defect report, acceptance report.

III OBJECTIVES

The objectives of this paper are as follows:

(1) To achieve a process control level of a defect rate of one percent or less.

(2) Feedback on process control problems.

(3) Obtain usable data for yield information and computer printouts.

III DISCUSSION

Step 9 (Figure 1) - Pre-Production Process Evaluation

Quality Inspection performs a 100% inspection for all characteristics on one CCA of each type produced. When total of defects is one percent or less (of defects possible), no corrective action is required. If the 1% level is exceeded, the wave solder supervisor is notified and corrective action is initiated.

Step 10 - Serialization of CCA's

The date of serialization (affixing lot number and serial number to CCA) is entered on the inspection traveler in "Date Serialized" block. Serialization occurs with a day two of manufacture.

Step 11 - First Inspection

Date Inspected, Work Authorization number, I.C. Date Code (if applicable), inspection stamp number, are all entered on the traveler. The inspector records the quantity of each defect in the column "@ 80" (Figure 2). Any rework required is performed then sent for re-inspection. This information is recorded in "Rework Quantity" column. The white (top) copy is the input document for the initial CCA inspection. Yield Charts for this operation are derived from this copy. Rework information can be utilized by Quality Engineering from the Yellow (second) copy.

Step 12 - Zehntel In-Circuit Test

Each CCA is subjected to an in-circuit analysis by the plantronics "zehntel" analyzer. Any CCA's with components found to be misloaded or otherwise non-compliant to the print are replaced and re-tested.

Step 13 - Functional (Powered-up) Test

Each CCA is subjected to a functional test where several parameters are measured. Components deficient at this operation are replaced and re-test is performed.

Step 14 - Final Inspection

The inspector records the quantity of each defect in the column "@120 (Fig. 3). This copy (pink copy) of the traveler is the final inspection input document.

Step 15 - Mandatory Customer Inspection (MCI)

Upon final acceptance of the CCA's by Quality, MCI is performed on an audit basis, traveler stamped off, and routed to stock.

Component Loading Surveillance

Whenever components are moved from the storage bin carousel to the manix loading trays, a Quality surveillance is performed (5Q on flowchart). An inspector verifies the correct part number for that tray. This is performed at the loading tray. This is an immense aid in reducing misloads. Within the last year, manufacturing has initiated a stamp system, whereby each person loading components has been issued a stamp with a letter unique to that person. The letter "A, B," etc. impression is made on an IC or Transistor (Pre-Selected Location) on each board type.
Additionally, when a new film cassette is installed on the manix system, an inspector verifies the correct cassette is installed.

Wave Solder Surveillance

Daily logging is performed on the preheat temperature, solder pot temperature, and flux specific gravity.

V CONCLUSIONS

How well have the objectives been met. Re-stated, they are as follows:

1. To achieve a process control level of a defect rate or one percent 1% or less.

2. Feedback on process control problems.

3. Obtain usable data for Yield information and computer printout.

Objective (1)

Currently on our program, there are three (3) different circuit card types. We have been able to achieve this level on all three types. However, there is always the possibility during pre-production process evaluation (step 9 Fig. 1) that the CCA sampled is not representative of the run. This has happened several times. In these cases the overall rate might be higher. Perhaps two boards per pallet might be sampled to determine better the defect rate for the run.

Objective (2)

By reviewing the Pre-production evaluation and first inspection results, very timely feedback has been obtained. When this information is offered as a computer printout (Figure 5), much information can be utilized such as: how many of a certain defects(s) per a time period, total defects per time period, if an inspector is suspending or acception more or less that the other inspectors, defect trends (are certain defects more prevalent at certain times versus others.)

Objective (3)

The data obtained on the printout is transferred to form a yield chart (Figure 4). This is used for our weekly Production-Reliability meeting with key personnel form Quality Engineering, Production Engineering, Program management and Reliability Engineering.

What problem areas exist to prevent objectives from being met.

Solderability of components, as everyone at this seminar is aware, continues to be a problem. S.B.R.C. requires at least a "95 percent coverage of solder in the affected area" per MIL-STD-202, method 208, (except transistors which only require 90 percent coverage.) Even with this tight requirement, (pre-tinning of leads (step 2. - Flowchart)) some dewetting, etc. still exists. It is ABSOLUTELY ESSENTIAL that the above requirements be maintained, it is the policy of our Quality Engineering Department that solderability results be audited by Quality Engineer on a frequent, continual basis. Flux specific gravity and solder purity (30-Day analysis frequency) must be carefully monitored.

VI ILLUSTRATION

THE SEQUENCE OF STEPS IN THE MANUFACTURE OF CCA'S

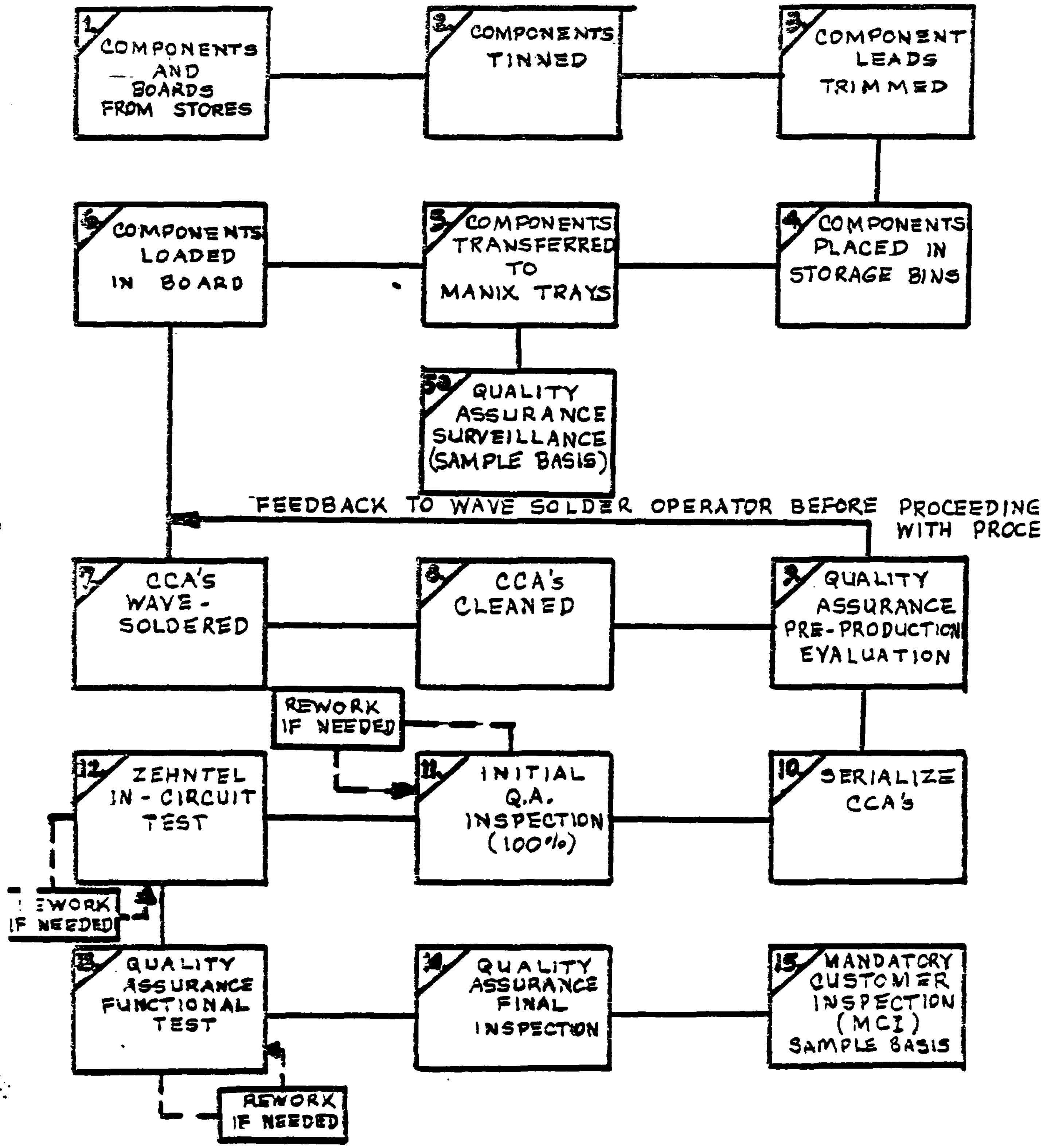


FIGURE 1.

TRAVELER-INSPECTION RECORD/SOLDER AUDIT
CCA, PREAMPLIFIER639 AS 3840 @ 490

W.A. NO	CARD NO	DATE SERIALIZED	DATE INSPECTED	W.O. NO	LOT NO.	MSN
L200	840	061582	061682	111244	10	350

I.C. DATE CODE						INSP
A1	8040	A2	8142	A3	8221	0120

	GROUP I DEFECTS REWORK REQUESTED	380	3120	REWORK QUANTITY 1	REWORK QUANTITY 2
001	Unsoldered connections				
002	Bridging				
006	Uninsulated wires or component leads routed over circuit path				
009	Rosin				
010	Cold solder				
011	Fractured or disturbed				
012	Insufficient solder				
013	Excessive solder · lead not discernible	1			
014	Poor wetting	1			
015	Overheating				
A15	Spattering				
016	Pits, holes, voids > 015 diameter				
018	Cut or nicked lead > 10% of dia. of wire or strand				
019	Stretched or scraped leads				
023	Improper stress relief				
026	Dewetting of solder area				
027	Slivers on circuit path				
031	Solder points, peaks, icicles	1			
033	Copper exposed on trimmed lead				
034	Excessive lead length	2			
035	Insufficient lead length				
037	Flux residue, oils, greases on assembly				
047	Component has improper clearance				
057	Component improperly located				
	GROUP I DEFECTS MRB REQUIRED				
008	Burned, scorched PWE or parts				
021	Pattern delaminated				
063	Blisters in conductor pattern				
064	Delamination of base material				
065	Wrinkles in conductor pattern				

	GROUP II DEFECTS * NO REWORK REQUIRED	380	≥120	REWORK QUANTITY 1	REWORK QUANTITY 2
A13	Excessive solder · lead discernible				
A16	Pits, holes, voids < 015 diameter	1			
020	Unclean connection				
A23	Improper stress relief	2			
025	Dewetting on areas not to be soldered				
030	Solder not smooth and shiny				
A33	Visible bare copper or base metal in solder connection				
040	Improper lead wrap				
043	Improper lead bends, radius				
044	Improper lead bend clearance				
046	Component not centered				
049	Clearance between PWB and component > 005				
054	Possible component abrasion				
058	Improper terminal swaging PWB				
	MISCELLANEOUS DEFECTS				
070	Incorrect value/polarity				
071	Damaged/broken component				
072	Missing component				
077	Wrong component				
	*Corrective action required if Group defects exceed 10% of Total Characteristics 81 Corrective Action Ref				
	Group II Defect Total Initial Rework				
	OTHER				

TRAVELER – INITIAL INSPECTION

FIGURE 2.

TRAVELER-INSPECTION RECORD/SOLDER AUDIT
CCA, PREAMPLIFIER639 AS 3840 @ 490

W.A. NO.	CARD NO.	DATE SERIALIZED	DATE INSPECTED	W.O. NO.	LOT NO.	MSN
L 200	840	0 6 1 5 8 2	0 6 1 6 8 2	111 244	10	350

I.C. DATE CODE			INSP
A1 8 0 4 0	A2 8 1 4 2	A3 8 2 2 1	0 1 2 0

	GROUP I DEFECTS REWORK REQUESTED	Ø60	Ø120	REWORK QUANTITY 1	REWORK QUANTITY 2
001	Unsoldered connections				
002	Bridging				
006	Uninsulated wires or component leads routed over circuit path				
009	Rosin				
010	Cold solder				
011	Fractured or disturbed				
012	Insufficient solder				
013	Excessive solder - lead not discernible				
014	Poor wetting				
015	Overheating				
A15	Spattering				
016	Pits, holes, voids > 015 diameter				
018	Cut or nicked lead > 10% of dia. of wire or strand				
019	Stretched or scraped leads				
023	Improper stress relief				
026	Dewetting of solder area				
027	Slivers on circuit path				
031	Solder points, peaks icicles				
033	Copper exposed on trimmed lead		/		
034	Excessive lead length				
036	Insufficient lead length				
037	Flux residues, oils, greases on assembly				
047	Component has improper clearance				
067	Component improperly located				
	GROUP I DEFECTS MRB REQUIRED				
008	Burned, scorched PWB or parts				
021	Pattern delaminated		/		
063	Blisters in conductor pattern				
064	Delamination of base material				
066	Wrinkles in conductor pattern				

	GROUP II DEFECTS * NO REWORK REQUIRED	Ø80	Ø120	REWORK QUANTITY 1	REWORK QUANTITY 2
A13	Excessive solder - lead discernible				
A16	Pits, holes, voids < 015 diameter				
020	Unclean connection				
A23	Improper stress relief				
025	Dewetting on areas not to be soldered				
030	Solder not smooth and shiny				
A33	Visible bare copper or base metal in solder connection				
040	Improper lead wrap				
043	Improper lead bends, radius				
044	Improper lead bend clearance				
046	Component not centered				
049	Clearance between PWB and component > 008				
064	Possible component abrasion				
068	Improper terminal swaging PWB				
	MISCELLANEOUS DEFECTS				
070	Incorrect value/polarity				
071	Damaged/broken component				
072	Missing component				
077	Wrong component				
	*Corrective action required if Group II defects exceed - (10% of Total Characteristics) 41 Corrective Action Ref				
	Group II Defect Total Initial Rework				
	OTHER				

TRAVELER – FINAL INSPECTION

FIGURE 3.

YIELD CHART

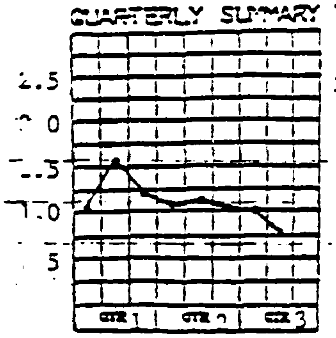
DSU 15 A/B

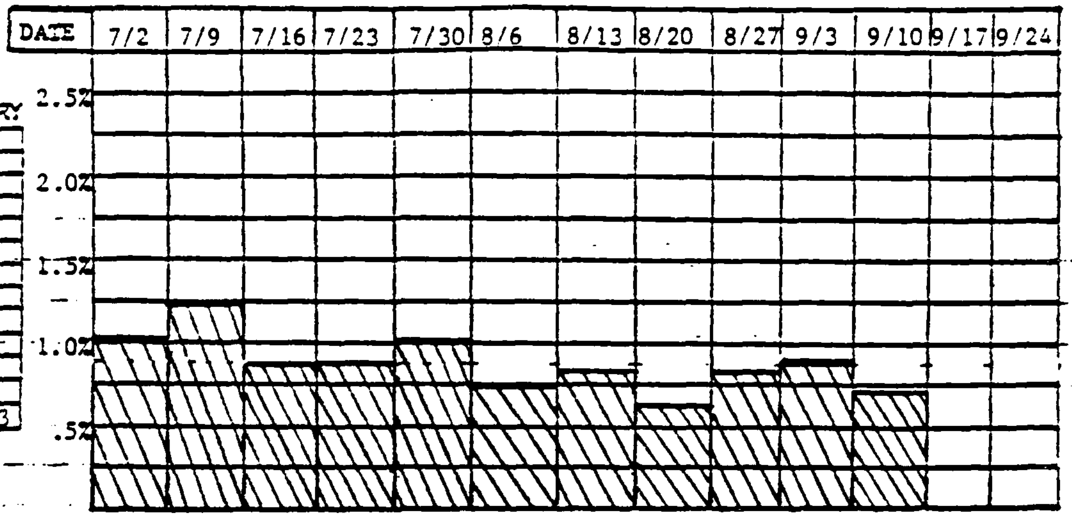
WEEKLY SOLDER SUMMARY CHART

SOLDER JOINTS REJECT RATE

SOLDER INSP., PREAMP

639AS3840 @ 490/80





DEFECTS

		7/2	7/9	7/16	7/23	7/30	8/6	8/13	8/20	8/27	9/3	9/10	9/17	9/24
1.	Insuff./Unsoldered	81	103	11	44	10	48	59	20	18	20	17		
2.	Poor wetting/Unwet.	335	267	102	141	233	123	141	39	68	15	88		
3.	Dist./Fract./Cold	39	26	11	22	49	13	68	6	12	4	4		
4.	Peaks/Pts./Icicles	9	4	5	5	19	23	4	1	3		2		
5.	Excess./Insuff./Lead Lgth	96	15	3	28	13	4	41		9	2	7		
6.	Shorting/Bridging	5		6	24	13	30	40	14	3	9	3		
7.	Incorr.Val./Polar.		1			1		1	1					
8.	Lifted pad/Trace.	1	2		1	1	1	6		7				
9.	Exp.Copper/Trmd.Lead	129	96	25	116	56	87	114	7	68	9	20		
10.	Other	165	137	65	79	64	104	211	56	158	21	49		

Prepared by:

DATE	LOT SIZE	TOTAL POSSIBLE DEFECTS	TOTAL DEFECTS	RATE - % SUSPENDED
7/2/82	202	82,820	960	1.04%
7/9/82	128	52,480	651	1.24%
7/16/82	65	26,650	229	.86%
7/23/82	130	53,300	460	.86%
7/30/82	107	43,870	464	1.06%
8/6/82	143	58,630	433	.74%
8/13/82	206	84,460	685	.81%
8/20/82	52	21,320	144	.68%
8/27/82	115	47,150	376	.80%
9/3/82	21	8,610	80	.93%
9/10/82	63	25,830	189	.73%

TOTAL # DEFECTS/BOARD = 410

FIGURE 4.

VII APPENDIX A

RECORD IDENTIFICATION

Card No	Last three digits of P/N (obtained for Inspection Traveler "CARD NO. Block).
Dateser	Date CCA serialized (obtained from Insp. Traveler "DATE SERIALIZED " Block)
Date Ins.	Date CCA first Inspected (@80). Obtained from Insp. Traveler "DATE INSPECTED" block).
WoNo	Work Order No. (obtained from "WO NO." block on Traveler
LotNo	Lot No. & Manufacturing Serial No. (MSN) obtained from Traveler "LOT NO. MSN" block.
DatCod	I.C. Date code, obtained from Traveler "I.C. DATE CODE" block.
Insp	Inspector Stamp No., obtained from traveler "INSP" block.
OpNo	Operation No. (@80 or @120), obtained from traveler @80 or @120 columns.

DEFECT IDENTIFICATION

Def 1	Defect, code no 001 (From Traveler)
Q 1	Quantity suspended for Def 1.
Def 2	Q2 etc.

VII APPENDIX A
DEFECTS PRINTOUT

INFORMATION TO BE PRINTED OUT

1. Lot Size
2. Total defects
3. Total defects possible
4. Defect rate (%)
5 Quarterly update for defect rate (%)

NOTE: Above to be obtained from oper. @80 and @120

ALGORITHYM

1. Lot Size No. CCA's inspected per week (NO. Records)

2 Total defects No. defects recorded per week (Q1 + Q2 + Q3 --------)

3. Total defects possible defects/CCA (constantper each CCA P/N) X CCA's per week.

4. Defect rate (% defects) total possible

$$\frac{\text{TOTAL DEFECTS}}{\text{DEFECTS/CCA X CCA's}} \text{ X } 100$$

5. Quarterly update ($\bar{x}$ Quar) = $\dfrac{\text{Defect Rate Month 1 + Def. Rate Month 2 + Def. Rate Mon. 3}}{3}$

NOTE: In addition to above, periodically the total No. of a particular defect(s) may need to be determined.

VII APPENDIX A
DEFECTS PRINTOUT

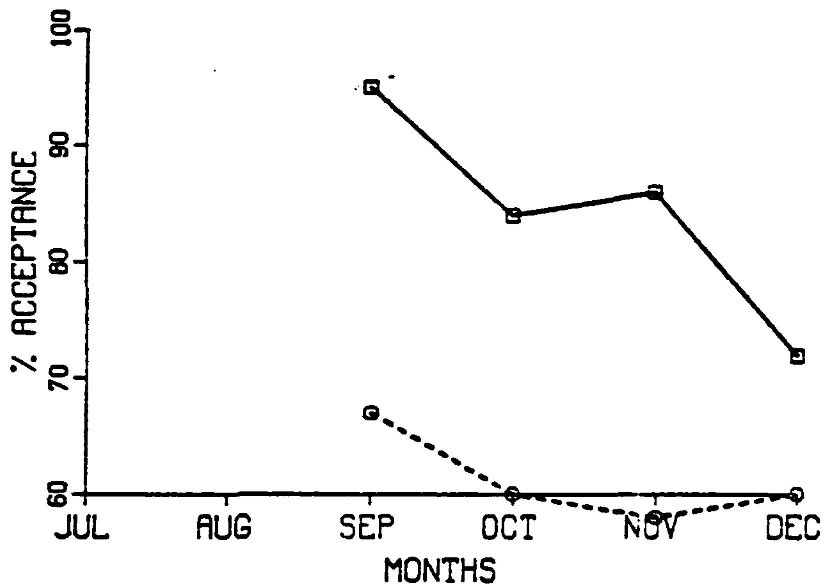
OP NUMBER	SUBMIT QTY	INSPECT QTY	ACCEPT QTY		DEF 1	DEF 1 QTY	DEF 2	DEF 2 QTY	DEF 3	DEF 3 QTY	DEF 4	DEF 4 QTY	DEF 5	DEF 5 QTY	DEF 6	DEF 6 QTY
30																
	1	1	1	100.00												
TOTAL	1	1	1	100.00												
390																
	1	1		.00	1487	1	1273	1								
TOTAL	1	1	0	.00												
410																
	3	3	3	100.00												
	8	8	8	100.00												
	8	8	8	100.00												
TOTAL	19	19	19	100.00												
530																
	4	4	4	100.00												
	11	11	11	100.00												
	14	14	11	78.00	2121	3										
TOTAL	29	29	26	89.00												
547																
	2	2		.00	2151	2										
	4	4	4	100.00												
	1	1	1	100.00												
	6	6	5	83.00	2111	1										
	10	10	9	90.00	2131	1										
	5	5	5	100.00												
	4	4		.00	2151	4										
	1	1	1	100.00												
	8	8	7	87.00	2122	1										
	19	19	19	100.00												
	1	1	1	100.00												
	12	12	11	91.00	2121	1										
TOTAL	73	73	63	86.00												
890																
	2	2	2	100.00												
	11	11	11	100.00												
	2	2	2	100.00												
	3	3	2	66.00	2153	1										
	1	1	1	100.00												

VII APPENDIX A
DEFECTS PRINTOUT

Date: 12-JAN-83
Report No: IDR001
QUALITY ASSURANCE ACCEPTANCE REPORT

ASSEMBLY NO:53792

LEGEND
□ OPERATION 670
○ OPERATION 680



	JUL	AUG	SEP	OCT	NOV	DEC
QUANTITY SUBMIT			21	78	68	37
QUANTITY INSPECT			21	78	68	37
QUANTITY ACCEPT			20	66	59	27
% ACCEPTANCE OPERATION 670			95	84	86	72
QUANTITY SUBMIT			59	116	140	122
QUANTITY INSPECT			59	116	140	122
QUANTITY ACCEPT			40	70	82	74
% ACCEPTANCE OPERATION 680			67	60	58	60

DEFECTS	JUL	AUG	SEP	OCT	NOV	DEC
02111				1	14	6
02121				1	12	3
02122					3	5
02123			1	2		1
02125				1	1	
02126					21	
02184				1	1	5
02230				1	1	
02231			1	2	1	2
02232			12	10	16	19
02233			2	1	1	4
02236			4	17	16	17

VII APPENDIX A
"CRT DISPLAY
FOR DATA ENTRY"

INSPECTION OBSERVATION RECORD

RECORD NUMBER	W/A NO.	W/E DATE	ORIGIN	PART NUMBER	EXTENDER
3489	L278	14-JAN-83		53782	400

LOT NUMBER	SERIAL NUMBER	LOT DATE	OPERATION NUMBER
	2432		40

INSPECTION PROCEDURE	SPECIAL DATA
52183	MARO 4532143-2

OPERATOR	SUBMIT	INSPECT	ACCEPT
184	10	10	7

DEFECTS

CODE	QTY
2113	1
2432	1
2324	1

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IX AUTHOR RESUME

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